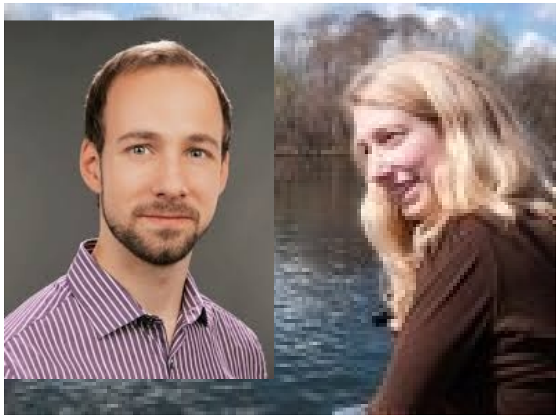
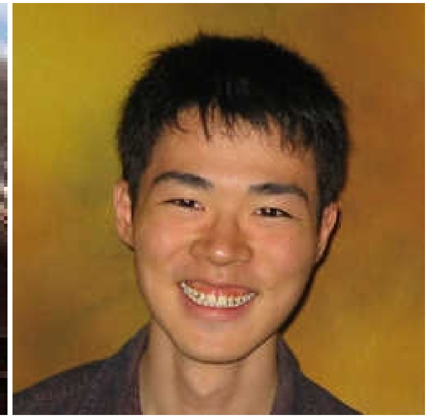
GWADW 2015, topologies&squeezing workshop summary H. Grote, L. Barsotti
LIGO-G1500712, May 21. 2015

Workshop (Excellent!) Speakers



Emil Schreiber (GEO)
Kate Dooley (GEO, now CIT)



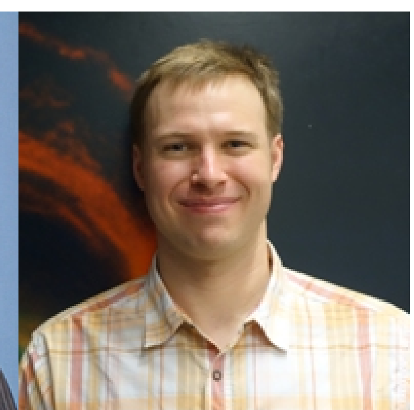
Tomoki Isogai (MIT)

Haixing Miao (Univ. of Birmingham)
Kentaro Somiya (Tokyo Inst. of Tech)

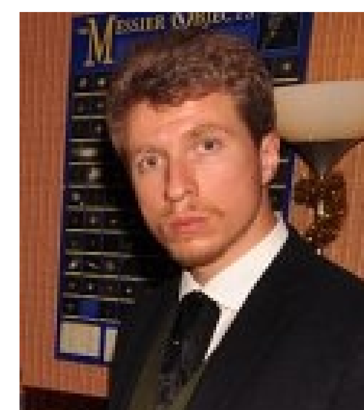
Jan Harms (Univ. of Urbino)

Giancarlo Cella (INFN Pisa)

Thomas Corbitt (LSU)



Adam Libson (MIT)



Stefan Danilishin (Univ of Glasgow)

Topologies and Squeezing “workshop style”

- Not many talks, half of the time dedicated to discussion
- Broad range of topics: from very technical to more theoretical (GOOD!)..although occasionally hard to engage everyone at the same time
- Effort to bridge between theory/experiment, maybe not always successful
- Discussion not pre-organized (some questions in mind, but leave the option to follow audience interest)

Topologies and Squeezing “workshop style”

- What can we do better?
- Different style to give people time to work on particular problems, and report back?
- For example: one “parallel workshop day” at the beginning of the conference, one at the end?

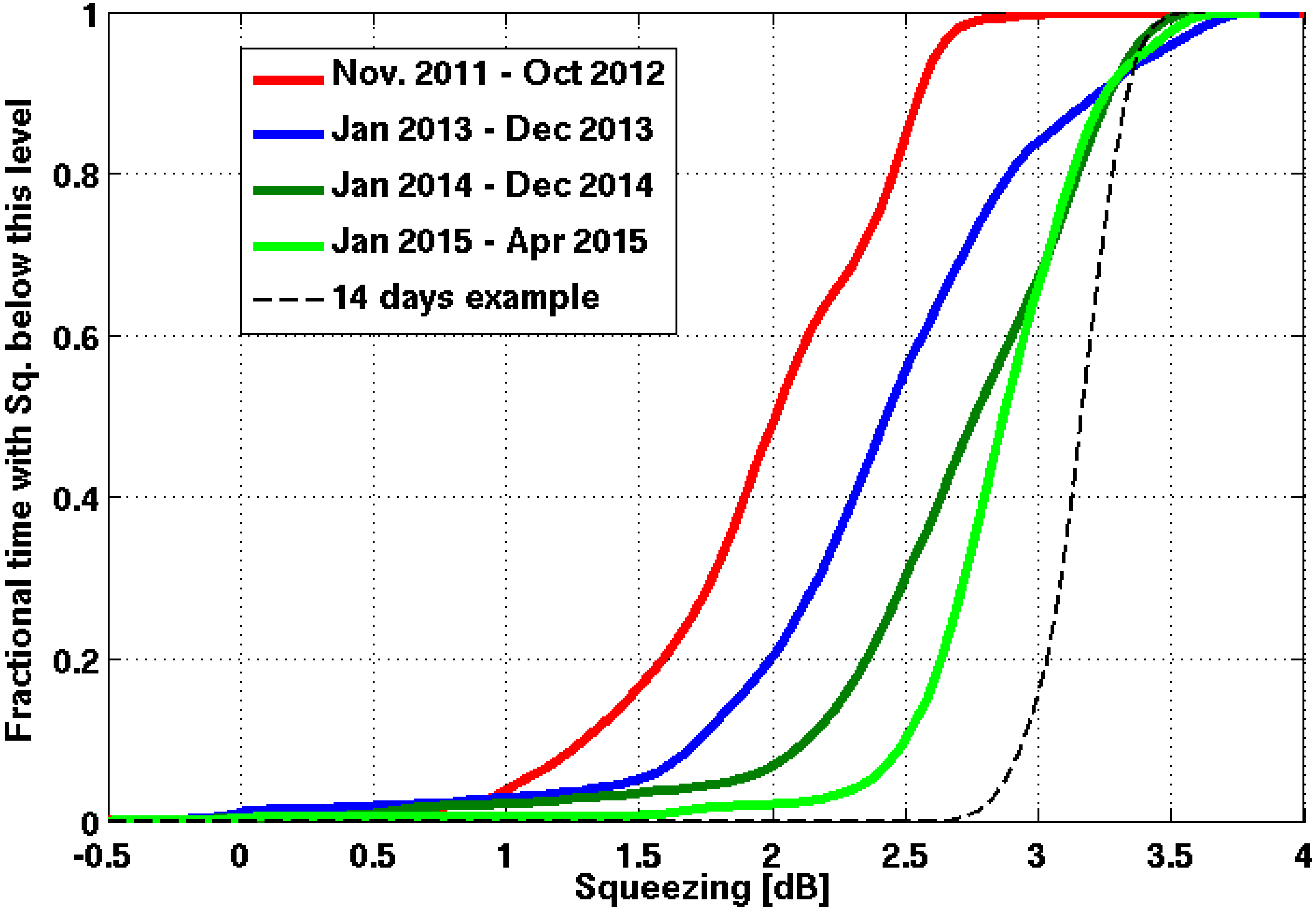
WIKI

- WIKI with supporting material (still work in progress):

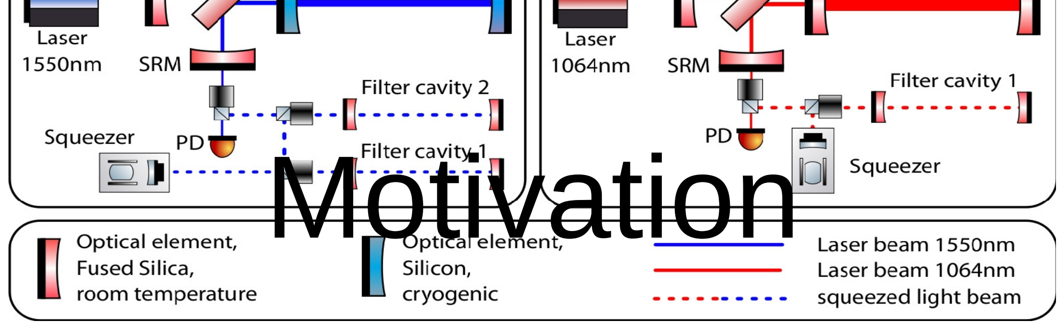
  https://wiki.ligo.org/AIC/TopSqz

The Road to 10dB

GEO long-term application of squeezing



Motivation



Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ T
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×10 km	2×10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}$ m/f^2	$5 \cdot 10^{-10}$ m/f^2
Gravity gradient subtraction	none	none

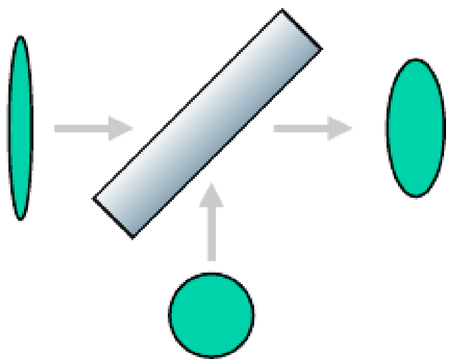
Table 10: Summary of the most important parameters of the ET-D high and low frequency interferometers. SA = super attenuator, freq. dep. squeez. = squeezing with frequency dependent angle.

ET-0106C-10

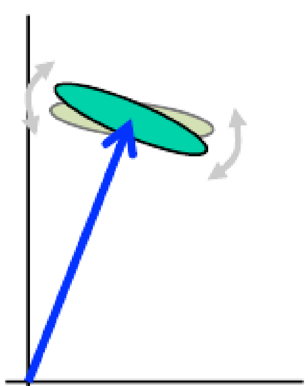
also, all LIGO strawman designs assume around 10 dB observed squeezing

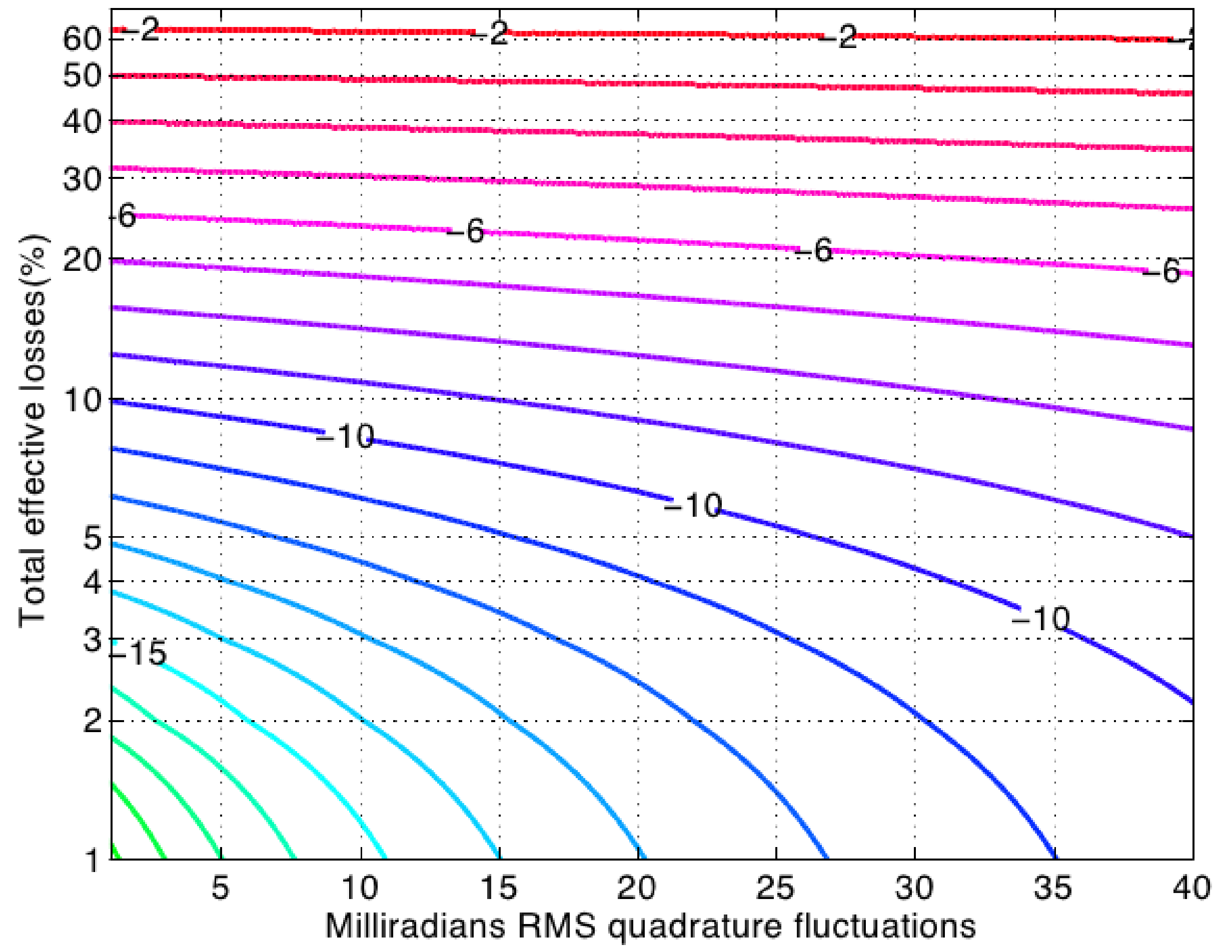
The main challenges

1. losses



2. phase noise





S. Dwyer et al., 2013

The road to 10 dB

- Motivation: 10dB observed squeezing assumed in ET design study and LIGO upgrades (straw red, >= Voyager)
- Challenges: 1. losses, 2. phase noise
- GEO loss budget: excess losses around injection Faraday and OMC. Too early to conclude on
- H1 loss budget: OMC loss, modematching, Faraday were large contributions
- GEO + H1 phase noise: ~35 mrad, perhaps some unknowns

Loss budget

component	achieved at GEO (at some point)	goal (numbers from Strawman Team Red)
OPA internal loss	5%	3%
Faraday isolator (rotator + 2 PBS')	4 · 2%	3 · 0.8%
loss on IFO reflection	1% (estimated)	1%
mode matching to OMC	4%	1%
OMC internal loss	2%	0.5%
PD quantum efficiency	1%	0.5%
filter cavity	–	1%
tap off	2 · 1%	–
total	21% (40% observed)	9%

source: ↑
LIGO-T1200046-v1

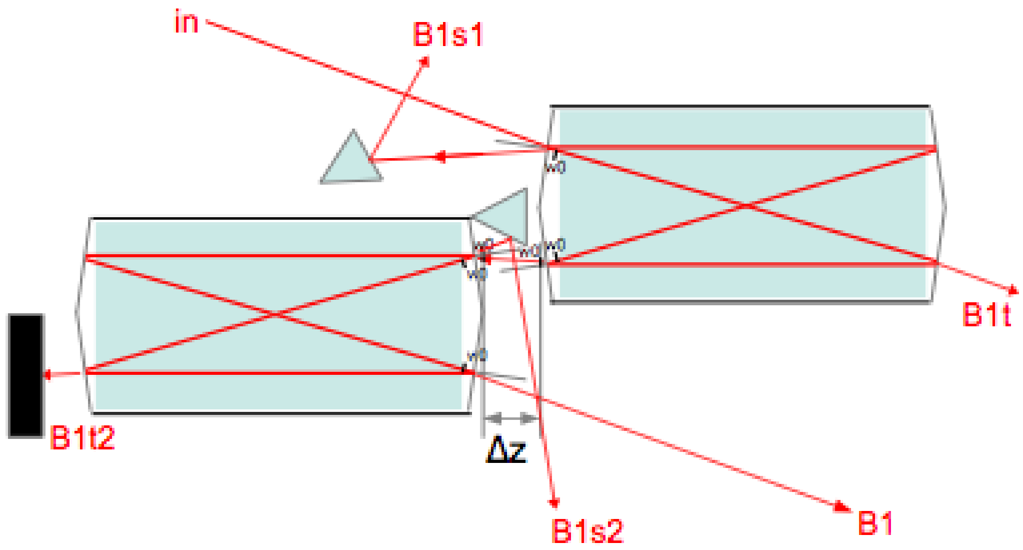
The road to 10 dB

- Need <= 10% total losses, <~ 5-15mrad phase noise
- Very challenging, but no clear showstopper yet
- Need to understand current excess losses
- R&D on: Faraday isolator (incl. PBSs), in-situ MM, OMC loss, PD-QE, filter cavity, integrated modeling of MM ...
- Need also to think in direction of IFO constraints: -OMC(s) design, aux. controls / pick-off minimization, other noises (det. electronics)
- balanced homodyne detection would help for: RF phase noise, back-scatter, electronics noise

2 OMCs a la Virgo?

Reduce losses and phase noise from RF sidebands

– 2 OMCs in series
-- low finesse low losses
-- double pole sufficient filtering of RF sidebands

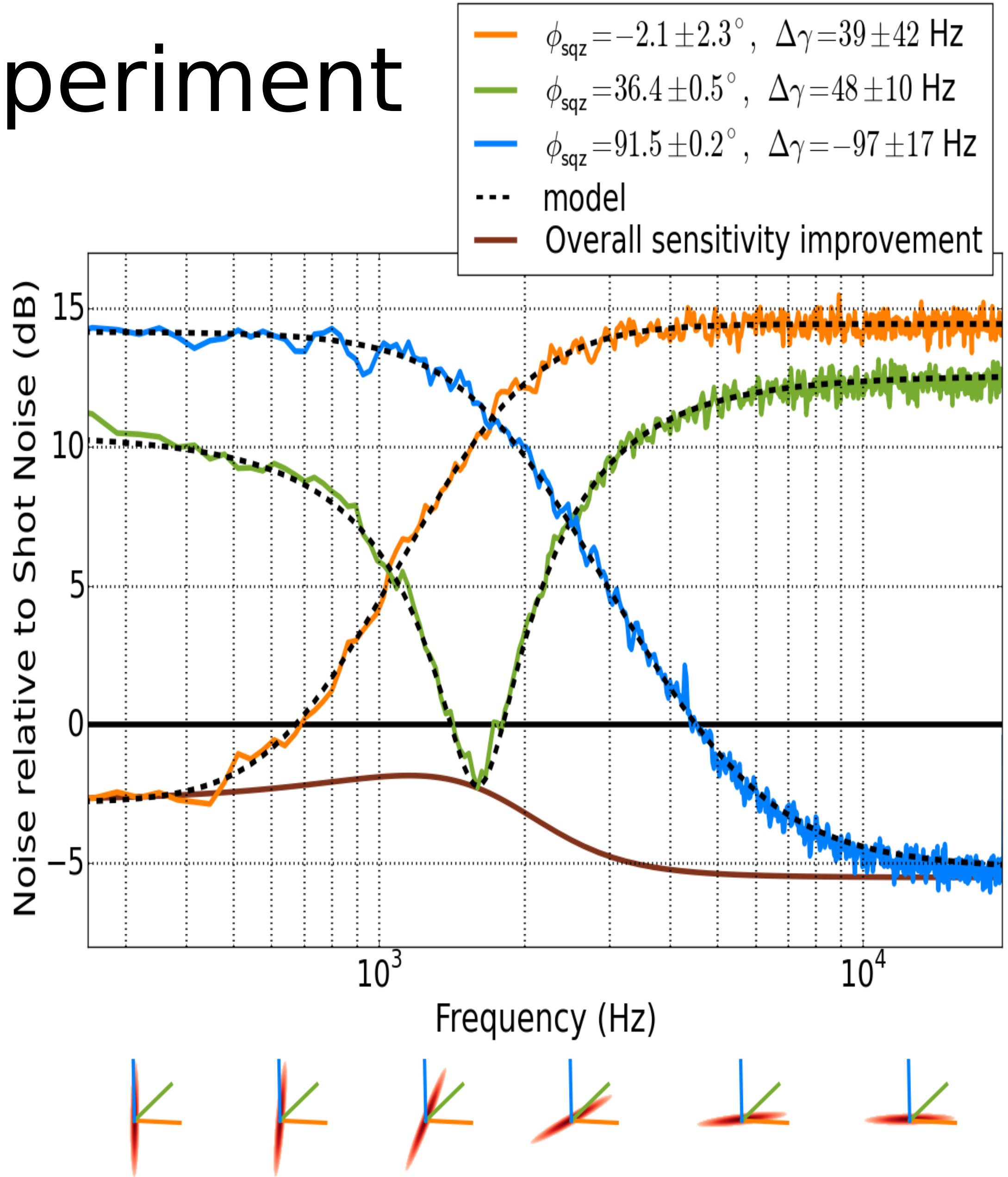


Virgo has already demonstrated 96% transmission through both OMCs

Advanced Virgo TDR
VIR–0128A–12

MIT Filter Cavity Experiment

- Cavity line width: about 1.2 kHz
- 5.5dB at high frequency, 2.5 dB at low frequency
- Frequency dependent squeezing is a potential early upgrade for aLIGO
- Verified that the model [1] accounts for most degradation factors



[1] P. Kwee et al. Phys. Rev. D 90, 062006 (2014).

The road to 10 dB
(at low frequencies)

- Frequency dependent squeezing:
- Principle demonstrated
- Length of filter cavity vs. low-freq. Squeezing: 100m → 5-6dB, 1km → 8-10dB, 4km → 9-11dB
- One more modematching
- Longer wavelength: roundtrip-loss reduced

Parameter Summary: getting to 10dB is challenging!

Parameter	Value
Filter cavity length	16 m
Filter cavity loss	16 ppm
Frequency-independent loss	10 %
Mode-mismatch (Squeezer – Filter cavity)	2 %
Mode-mismatch (Squeezer – Local oscillator)	5 %
Frequency-independent phase noise (RMS)	30 mrad
Filter cavity length noise (RMS)	0.3 pm
Injected squeezing	10 dB

Toward 10dB

Parameter	Value
Filter cavity length	4 km
Filter cavity loss	120 ppm
Frequency-independent loss	4 %
Mode-mismatch (Squeezer – Filter cavity)	1 %
Mode-mismatch (Squeezer – Local oscillator)	1 %
Frequency-independent phase noise (RMS)	5 mrad
Filter cavity length noise (RMS)	0.15 pm
Injected squeezing	18 dB

The road to 10 dB, summary

- Challenging, but not crazy to think of 10dB in >~10 years (at least HF)
- R&D ongoing
- At GWADW in 2010, S. Danilishin told us squeezing would be conventional 5 years from then (...now).
- Input squeezing with filter cavity is benchmark now


I dont believe it
Its a measurement

Where do we go from here?

Output filter / Variational output

Intra-cavity squeezer

White light cavities

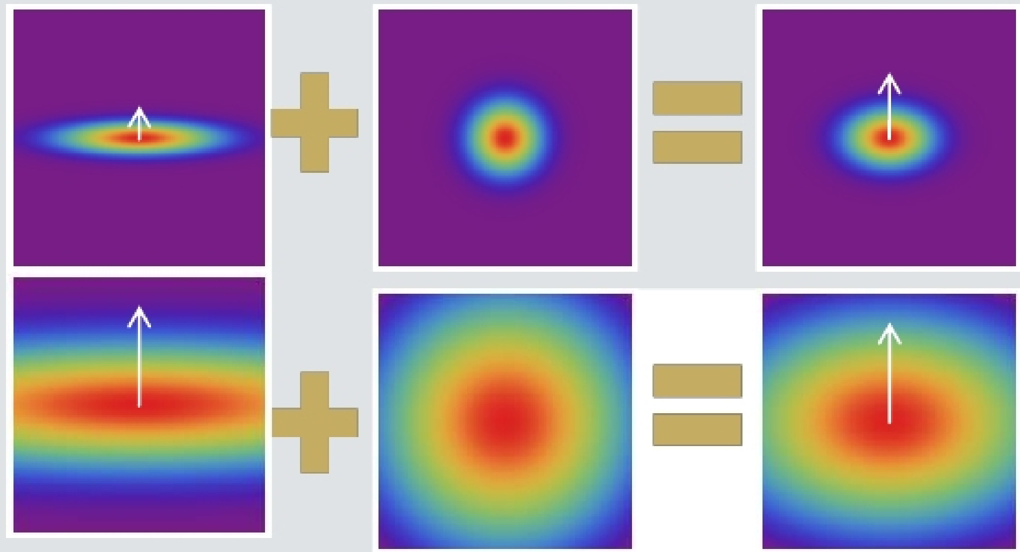
Opto-mechanical interaction

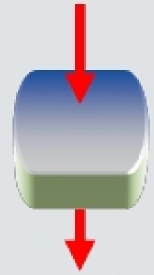
Speed meter configuration

Output anti-squeezer

Amplification and Quantum Mechanics

- **Most obvious approach:** amplify the signal <u>before</u> the losses
- **Naive implementation does not work** not compatible with Quantum Mechanics rules
- **Solution:** amplify one quadrature at the expense of the other

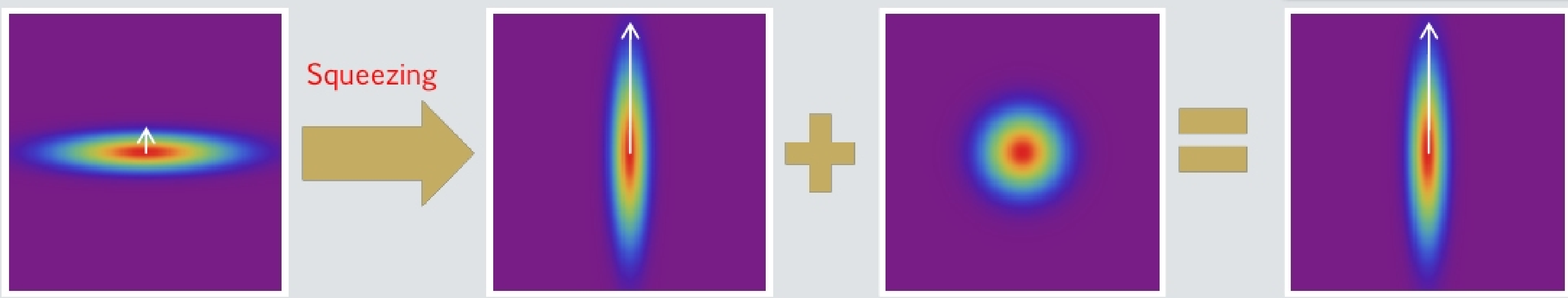




$$\hat{b} = \alpha\hat{a} + \beta\hat{a}_v + \gamma\hat{a}_v^\dagger$$

$$|\gamma|^2 = |\alpha|^2 + |\beta|^2 - 1$$

Additional fluctuations introduced unacceptable: squeezing is destroyed again

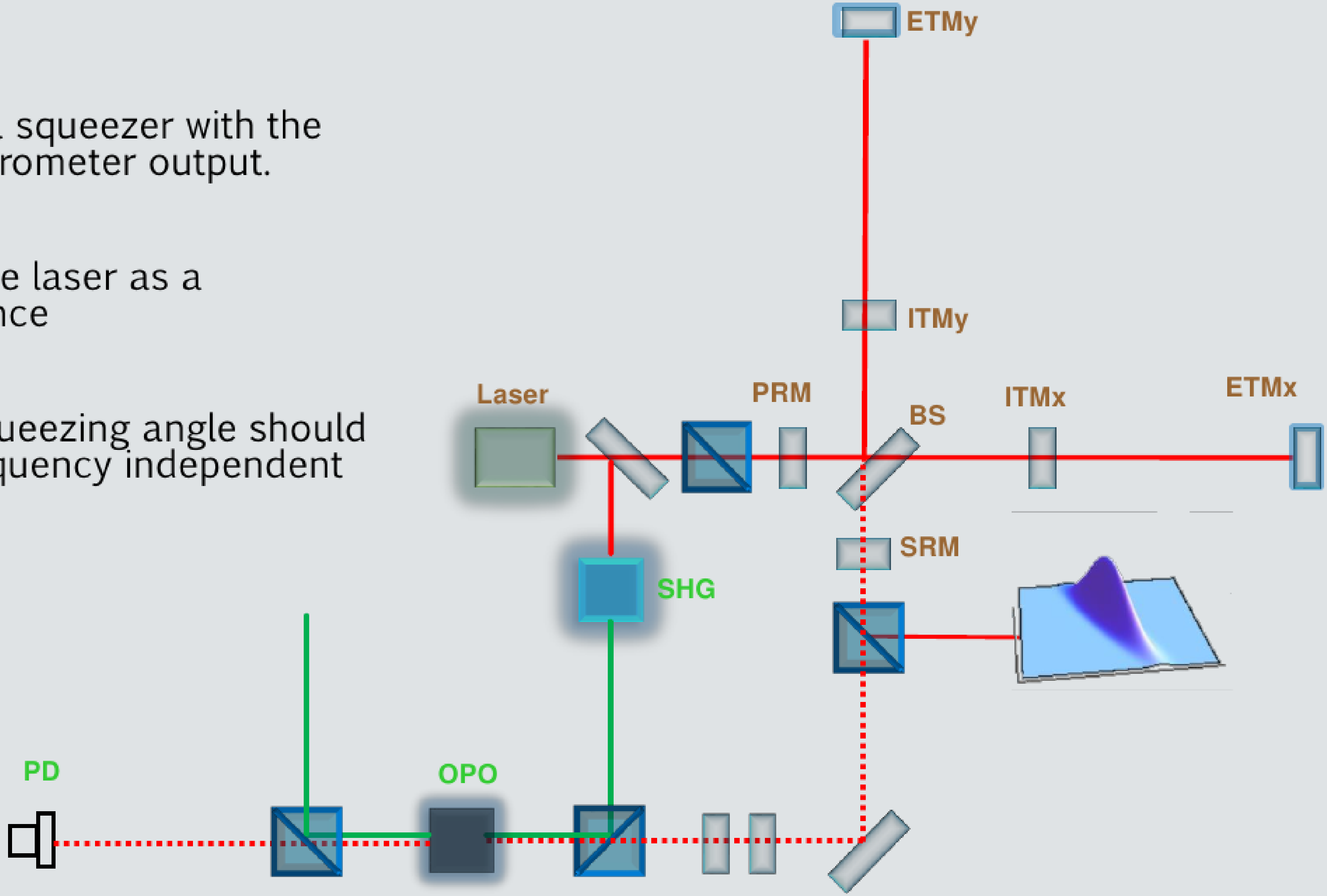


Implementation: nearly most obvious approach

Feed a squeezer with the interferometer output.

Use the laser as a reference

Antisqueezing angle should be frequency independent



...so obvious that it could not be new!

PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 15 August 1980)

Many thanks to Lisa for pointing me to the Khalili's presentation at CALTECH which contain the reference

https://dcc.ligo.org/LIGO-G1500313

So, I will add myself a philosophical slide

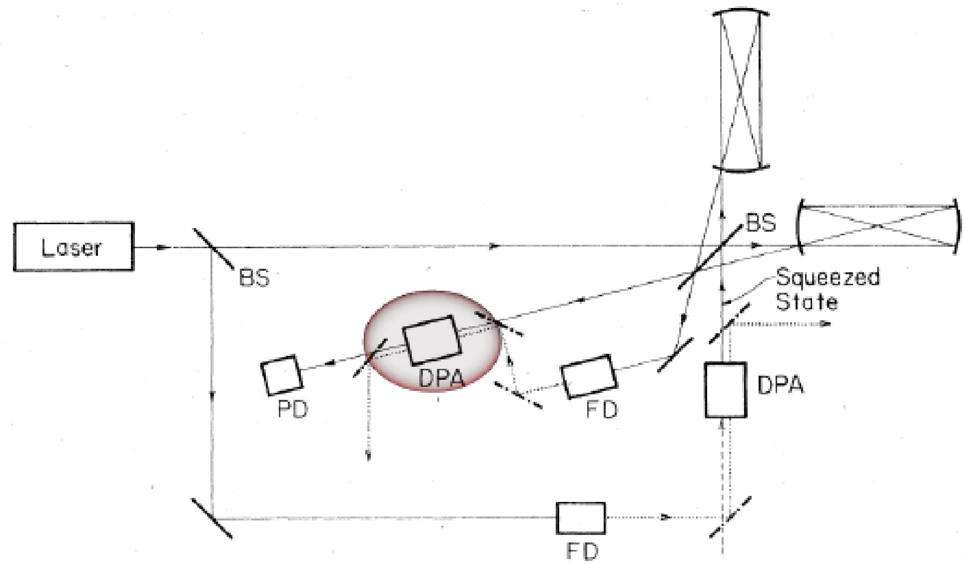


FIG. 4. Squeezed-state interferometer (abbreviations: BS=beam splitter; FD=frequency doubler; DPA=degenerate parametric amplifier; PD=photodetector). The crucial feature of the squeezed-state technique is the DPA located in the normally unused input port. This DPA takes the vacuum fluctuations incident on it (dashed arrow) and produces a squeezed state. To pump the DPA, one uses light that is extracted from the laser beam at a beam splitter and then doubled in frequency. There is another DPA in one of the output ports. This output DPA squeezes the light in that port, which is near a null in the fringe pattern, and thereby matches the noise in the light to the shot noise in an inefficient PD. The output DPA is pumped by frequency-doubled light from the other output port. The laser operates at frequency ω. Light beams at frequency ω are drawn with thin lines, and the components for handling them are drawn with heavy lines. The pump beams at frequency 2ω are drawn with dotted lines, and the mirrors for routing them are drawn with heavy, broken lines. These mirrors are assumed to transmit at frequency ω.

Output Anti-squeezing

- Idea: amplify signal and noise before losses degrade squeezing
- Originally conceptualized by Caves for low-PD QE
- Now re-evaluated also for OMC / MM losses
- However: OPO might need cavity (MM...) which would become circular...
- Do we really have to fight OMC loss with this technique?
- Lets keep it in mind if we get trouble with 10dB

Where do we go from here?

Output filter /
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White light cavities

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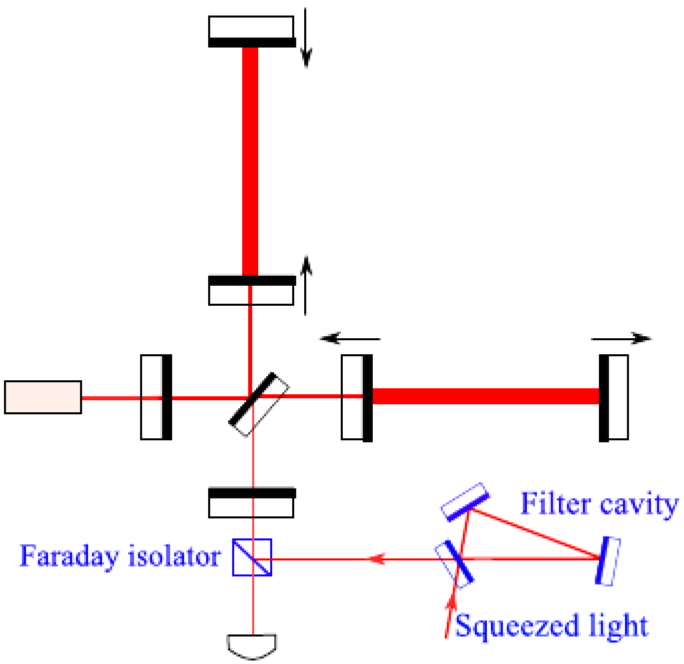
Speed meter configuration

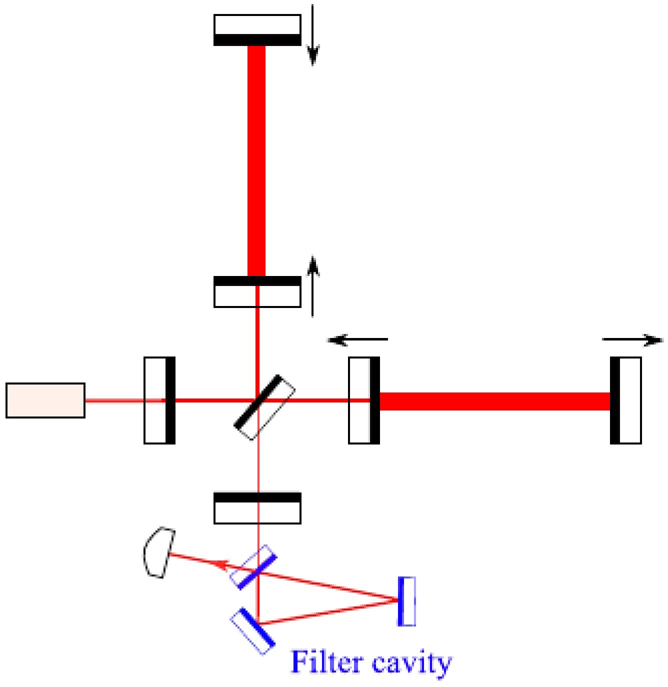
Output anti-squeezer

Output filter

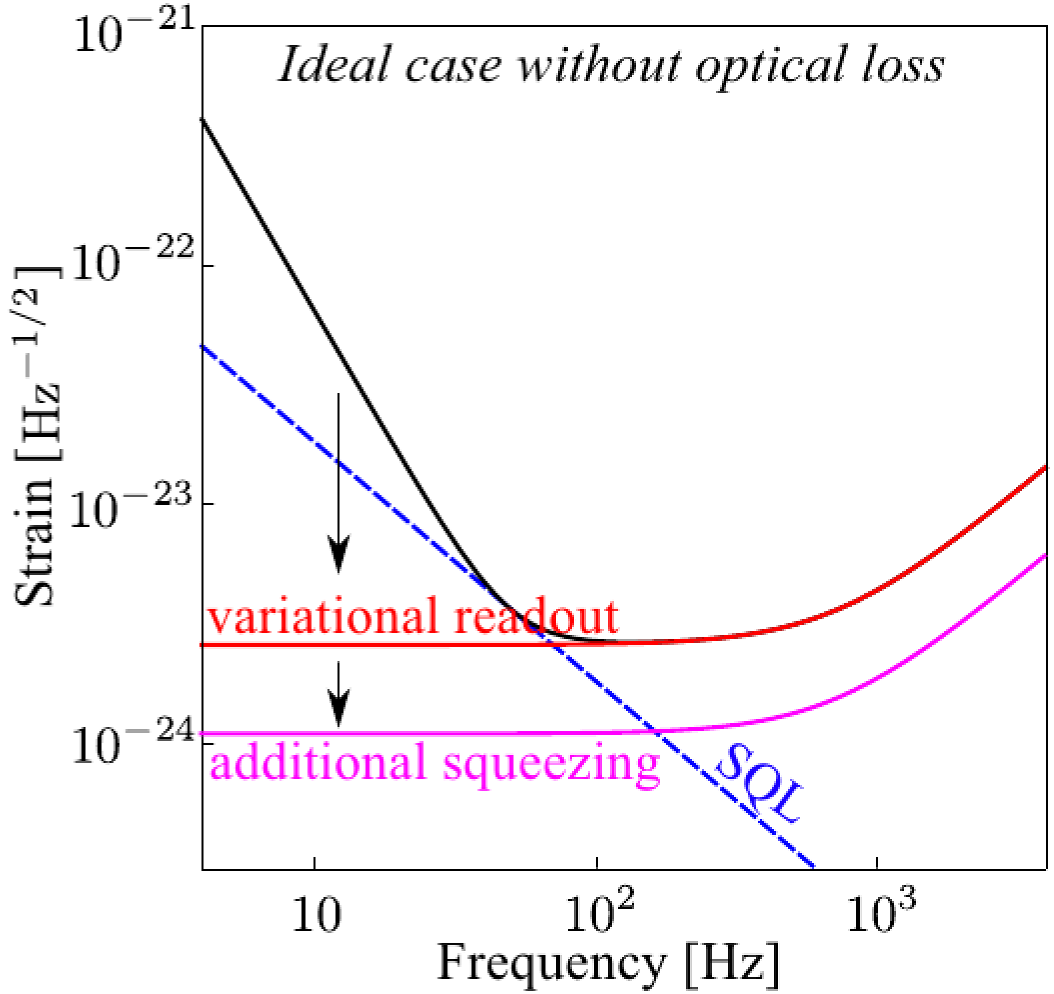
Input filter



Output filter

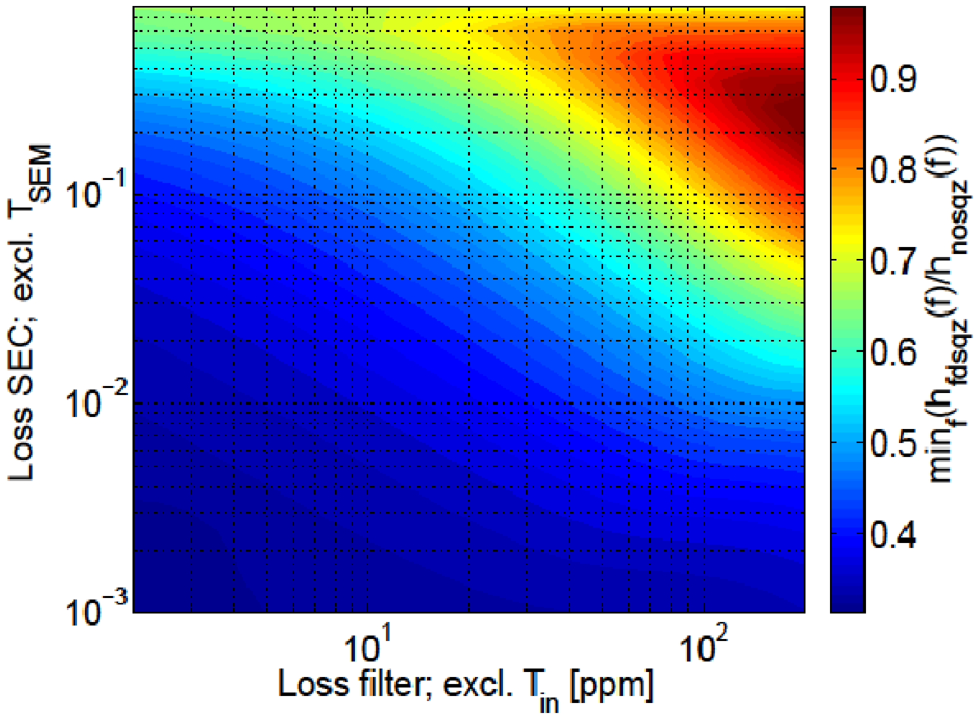


Output filter

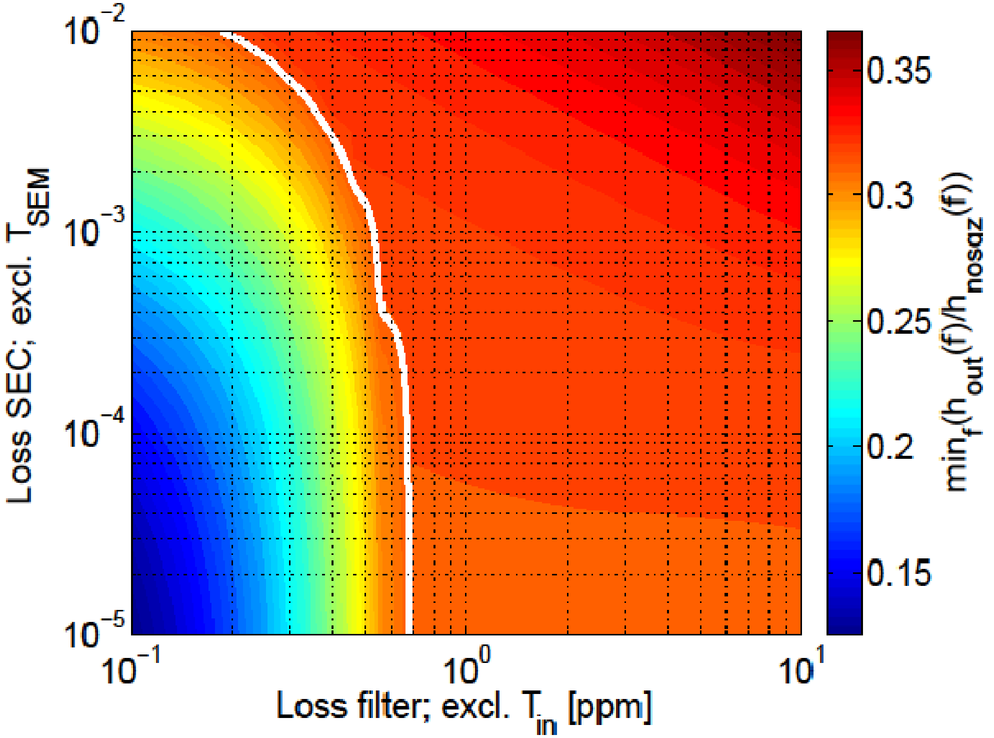


Output filter

Input filter



Output filter



Example: 16m filter cavity

Output filtering

- For 16m filter cavity, probably not feasible (need 2ppm round-trip loss)
- Even more stringent requirements: losses of arm cavities
- Perhaps for later generation, very long filter cavity
- → R&D work on mirror losses: surface roughness, point defects. (surface roughness probably dominates losses)
- → design cavity to minimize clipping loss

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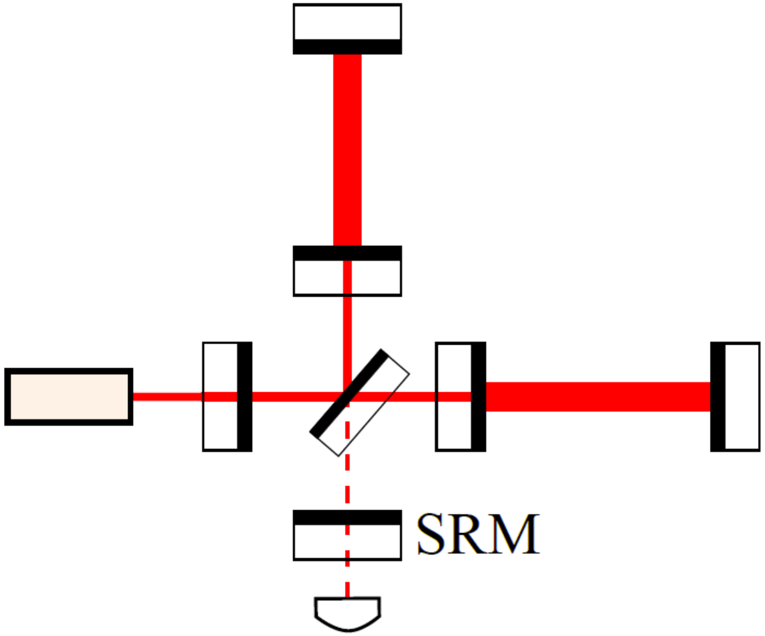
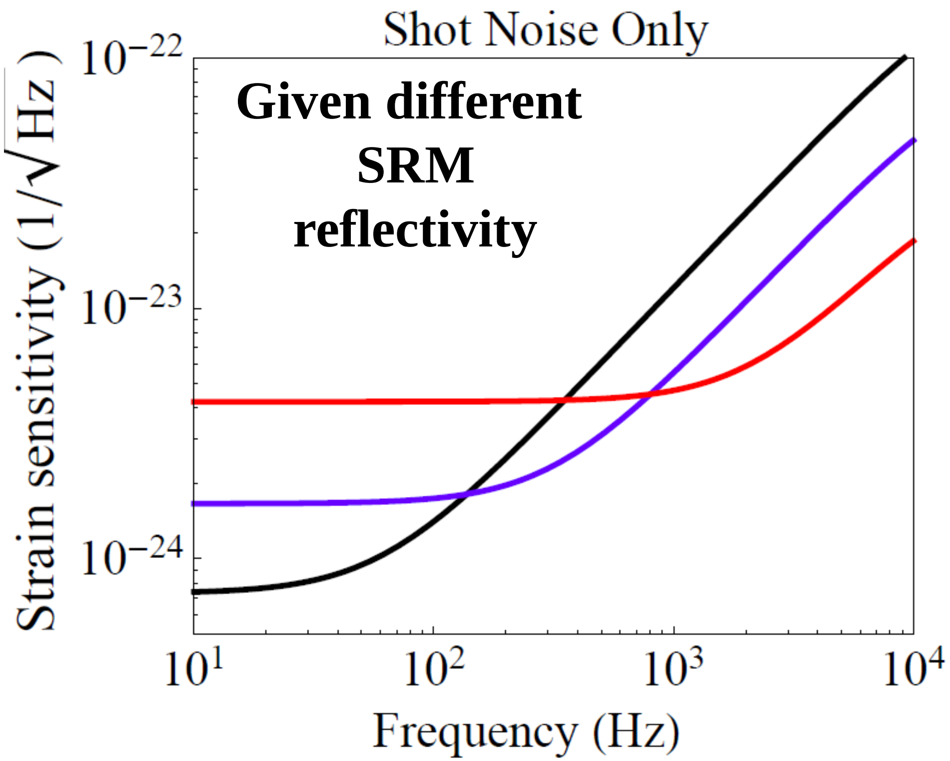
Mizuno Limit

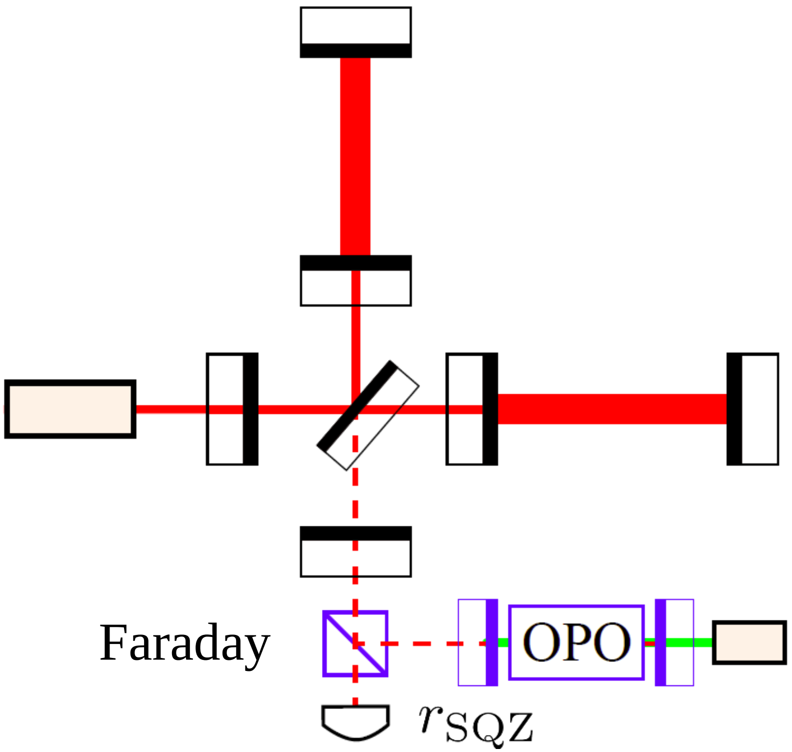
Shot-noise-limited sensitivity and signal recycling:

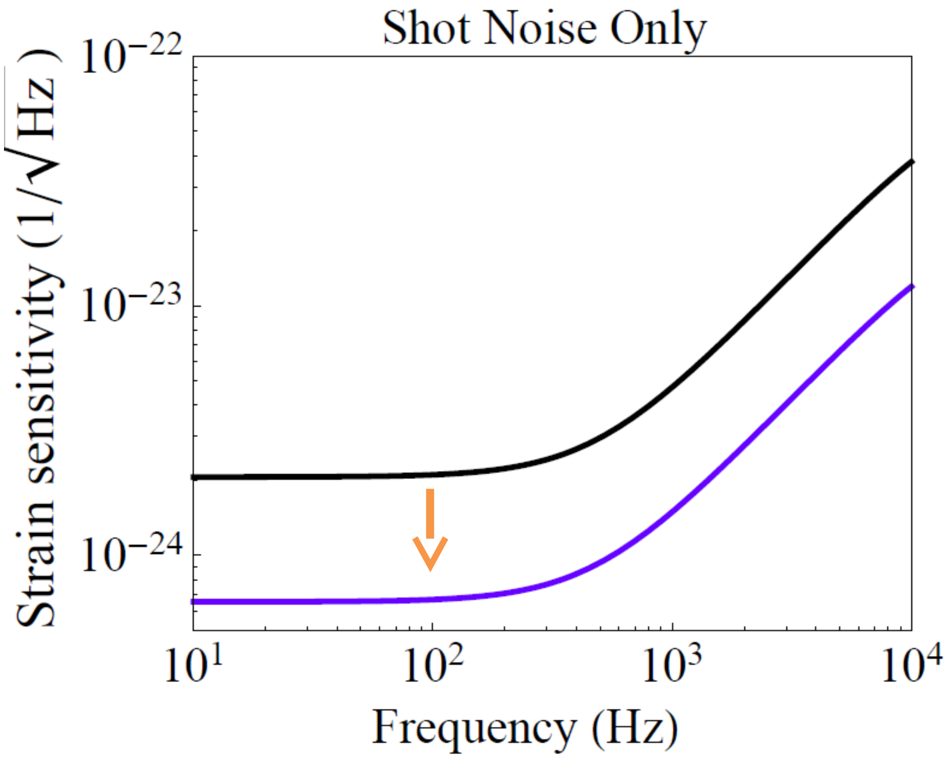




Approaches for Surpassing Mizuno Limit

Peak-sensitivity oriented: external squeezing





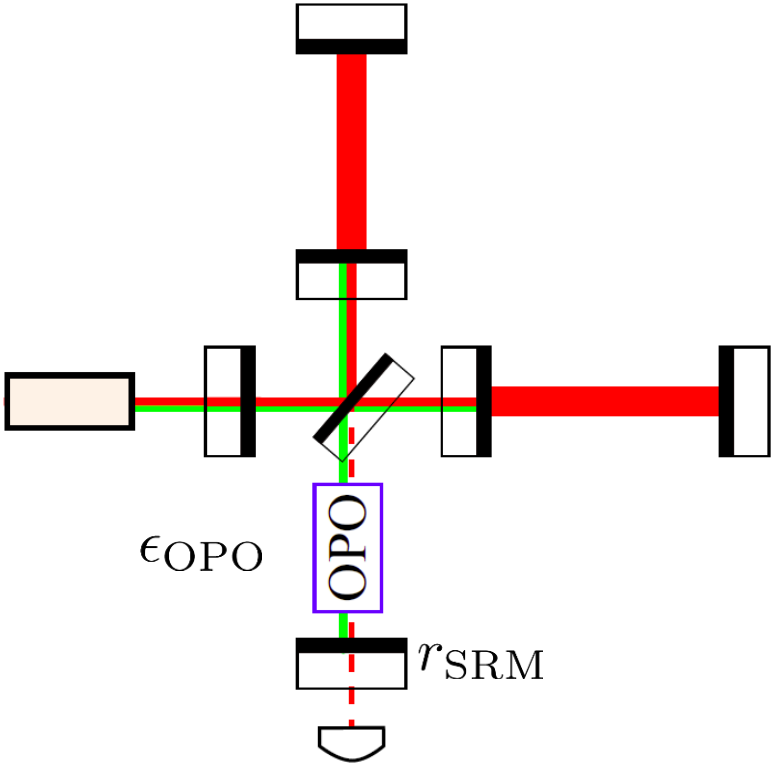
Challenge: optical loss of injection path

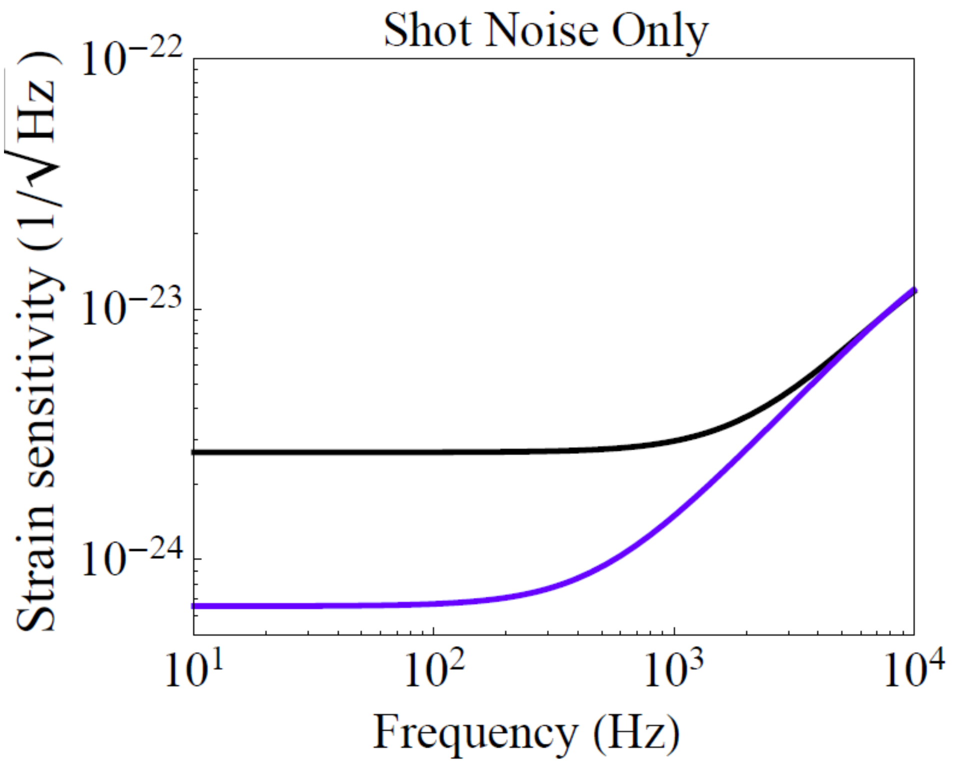
Max Mizuno beating factor:

$$\int \frac{d\Omega}{S_{hh}^{\mathrm{sqz}}(\Omega)} \Big/ \int \frac{d\Omega}{S_{hh}(\Omega)} \approx \left(\frac{\epsilon_{\mathrm{OPO}}}{1 - r_{\mathrm{SQZ}}^2} + \epsilon_{\mathrm{injection}} \right)^{-1}$$

Approaches for Surpassing Mizuno Limit

Peak-sensitivity oriented: internal squeezing





Challenge : optical loss of the nonlinear crystal

Max Mizuno beating factor:

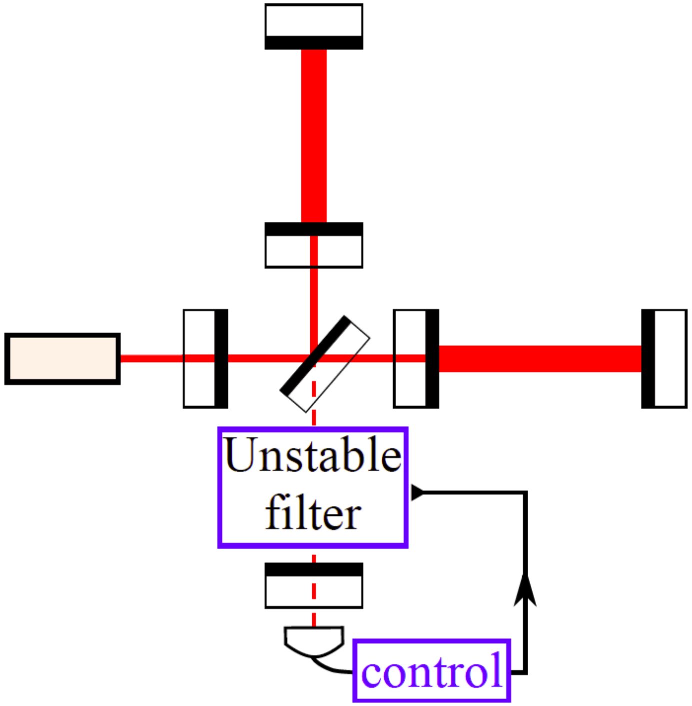
$$\int \frac{d\Omega}{S_{hh}^{\rm sqz}(\Omega)} \Big/ \int \frac{d\Omega}{S_{hh}(\Omega)} \approx \left(\frac{1-r_{\rm SRM}^2}{\epsilon_{\rm OPO}}\right)^{1/2}$$

Reference: Mikhail Korobko & Roman Schnabel *et al.*, in preparation

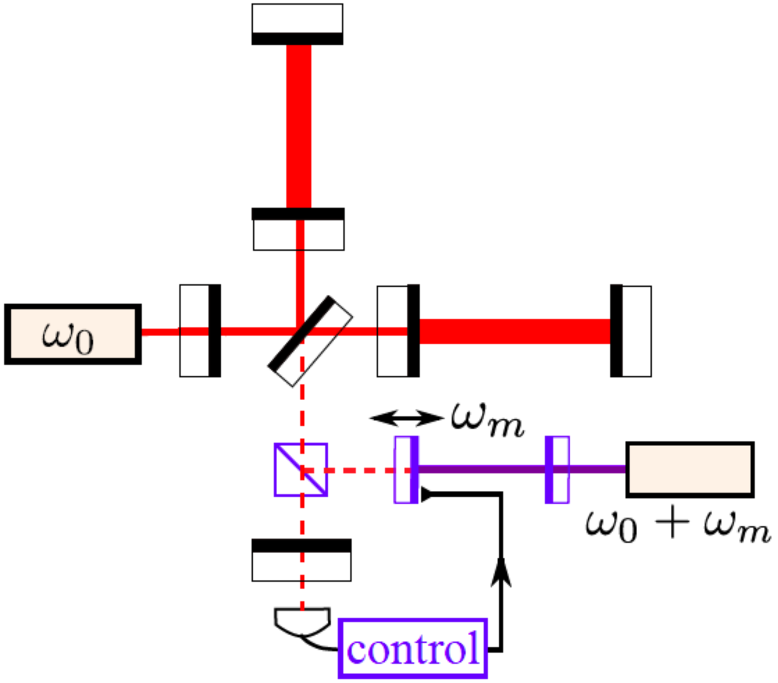
Approaches for Surpassing Mizuno Limit

Bandwidth-oriented: white-light-cavity ideas

Case II:



An example using optomechanics:



Challenge: thermal noise from mechanical oscillator (optomechanics)

$$\frac{k_B T_{\rm envir}}{Q_m} < \hbar \gamma_{\rm SRM}$$

Fundamental Quantum limit

$$\mathrm{SNR}_{\max} \le \frac{M^2 L_{\mathrm{arm}}^2}{\hbar^2} \int d\Omega\, |h(\Omega)|^2 \Omega^4 |R_{xx}(\Omega)|^2 S_{FF}^{\mathrm{quant}}(\Omega)$$

Applied to tuned configurations (no optical spring):

$$R_{xx}(\Omega) = -1/(M\Omega^2) \qquad S_{FF}^{\mathrm{quant}}(\Omega) = S_{PP}(\Omega)/c^2$$

With matching filtering:

$$\mathrm{SNR}_{\max} = \int \frac{|h(\Omega)|^2}{S_{hh}^{\mathrm{quant}}(\Omega)} d\Omega$$

Leading to a generalized Mizuno limit [$h(\Omega) = 1$ **]:**

$$\int \frac{d\Omega}{S_{hh}^{\mathrm{quant}}(\Omega)} \le \frac{L_{\mathrm{arm}}^2}{\hbar^2 c^2} \int d\Omega\, S_{PP}(\Omega) = \frac{L_{\mathrm{arm}}^2}{\hbar^2 c^2} V_{PP}$$

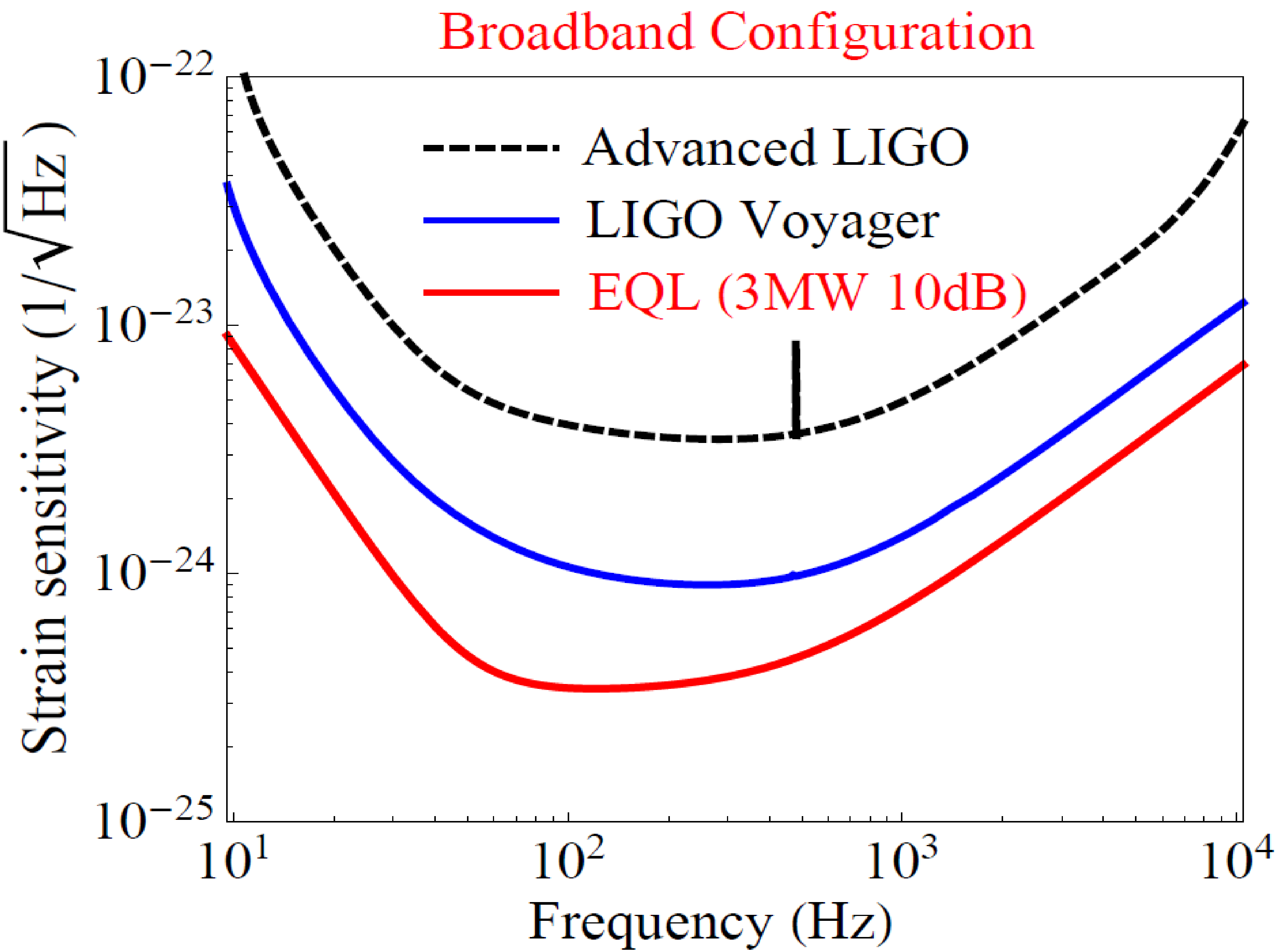
(variance of power fluctuation)

Upper sensitivity bound for all schemes with squeezing and WLC.

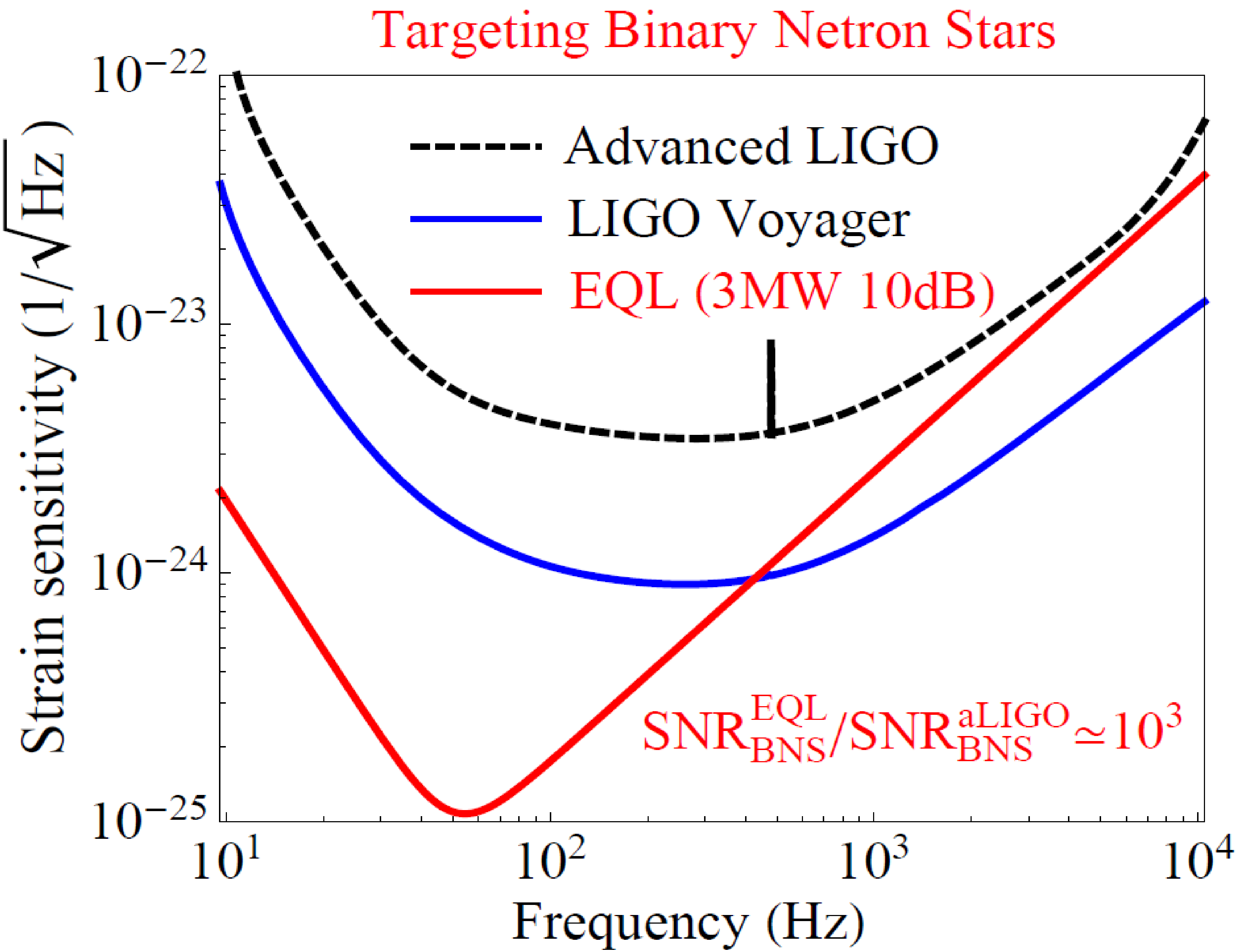
Fundamental quantum limit

- Mizuno limit (stored energy)
- Standard quantum limit (mass, power)
- → combine to fundamental quantum limit
- Perhaps can help answer the question: “given a source we want to match, and given some power and squeezing, how much better could we do than we do?

Fundamental Quantum limit: An Example



Fundamental Quantum limit: An Example



Where do we go from here?

Output filter /
Variational output

Intra-cavity squeezer

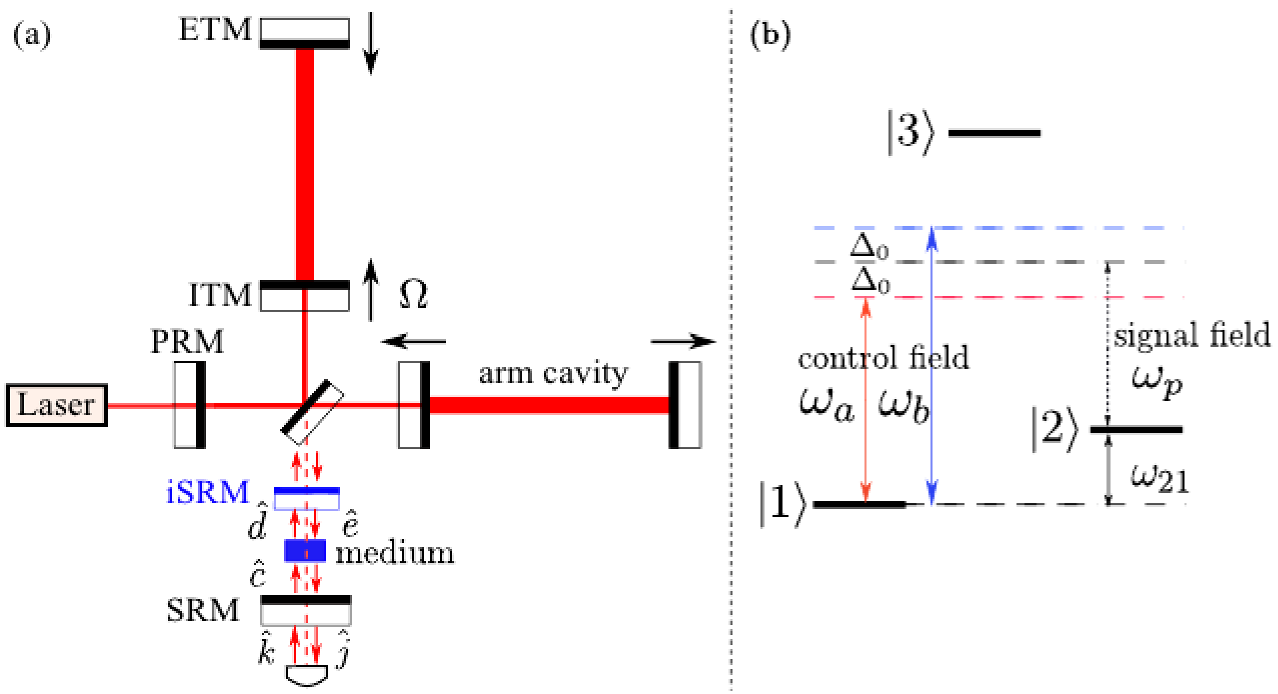
White light cavities

Opto-mechanical interaction

Speed meter configuration

Output anti-squeezer

White light cavities: Atomic media



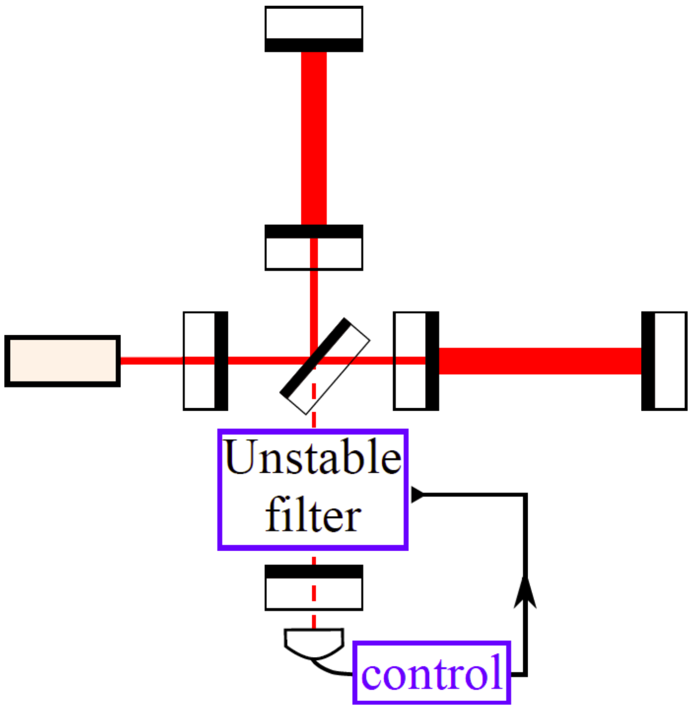
White light cavities

- White light cavity atomic media ready in 10-20 years? →H.Müller: ”hard to say, atomic media are dirty systems. Perhaps, if someone works on it dedicatedly to make it work”

Approaches for Surpassing Mizuno Limit

Bandwidth-oriented: white-light-cavity ideas

Case II:



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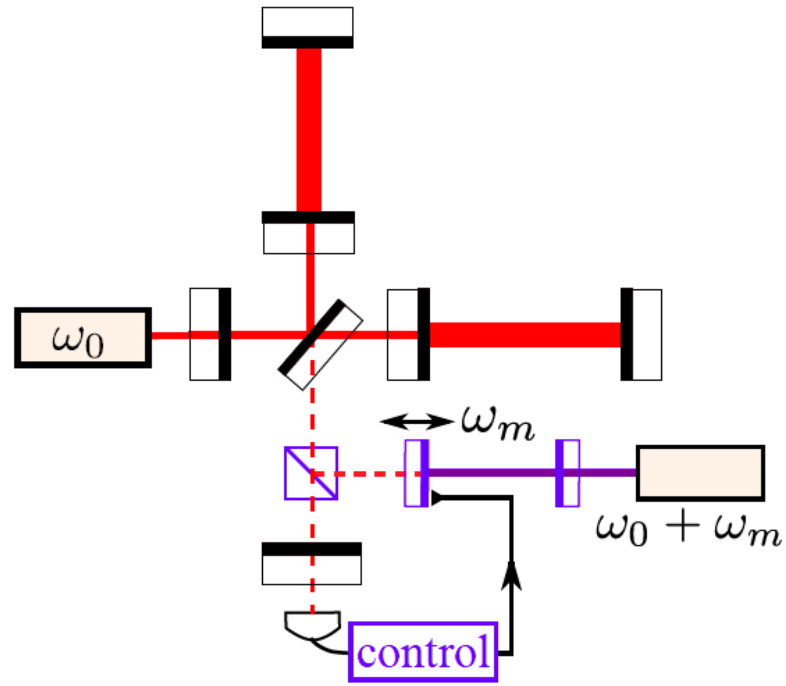

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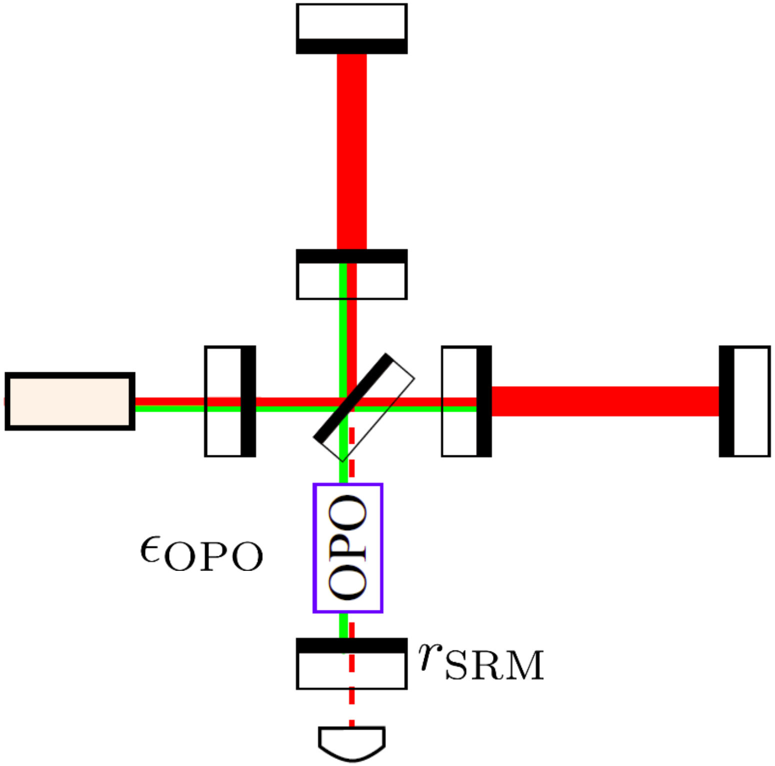

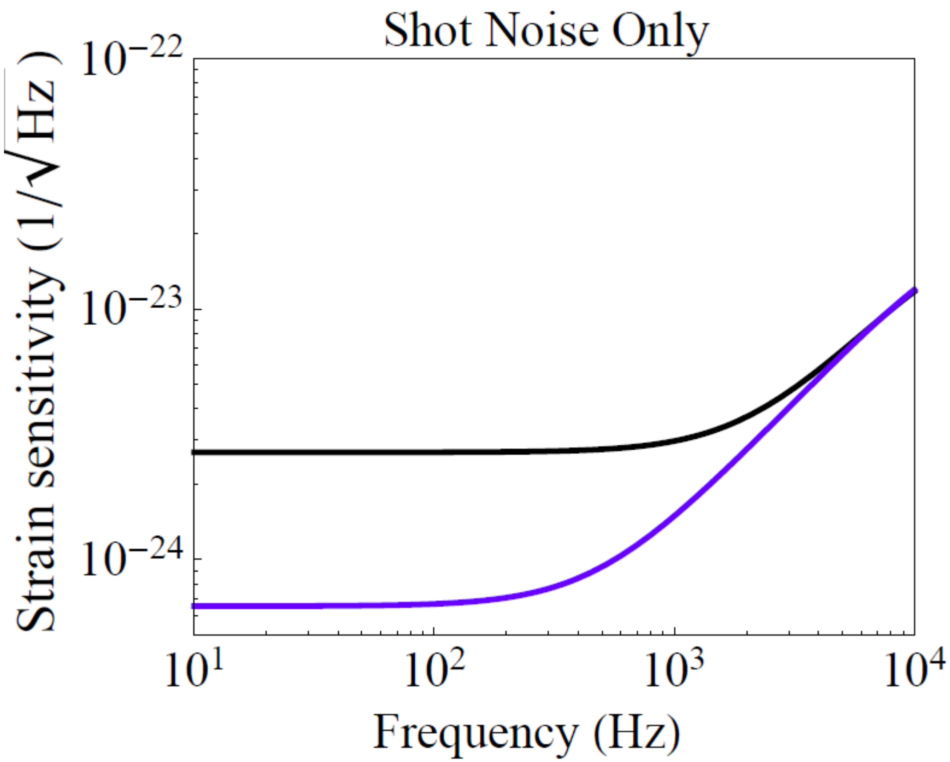

Challenge : optical loss of the nonlinear crystal

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Reference: Mikhail Korobko & Roman Schnabel *et al.*, in preparation

Intra-cavity squeezing

- Intra-cavity squeezing: can be interesting if single-pass loss at OPO is <~ 1%. Mode matching to pump beam does matter...

  (Miao & Somya to agree)

- But can we conceive of big crystals, OPO modematching in the SR cavity?

Where do we go from here?

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Variational output**

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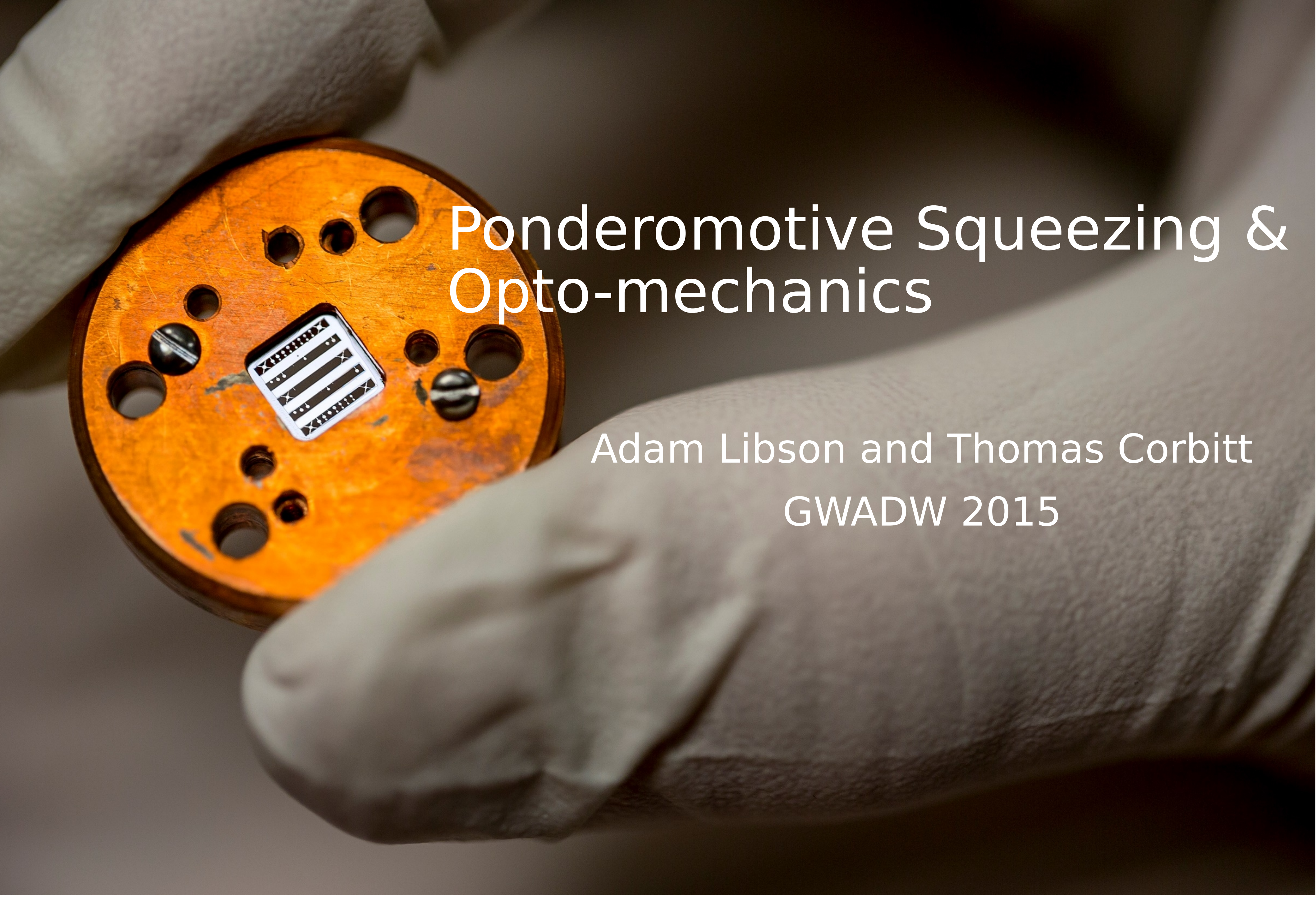
Output anti-squeezer



Ponderomotive Squeezing & Opto-mechanics

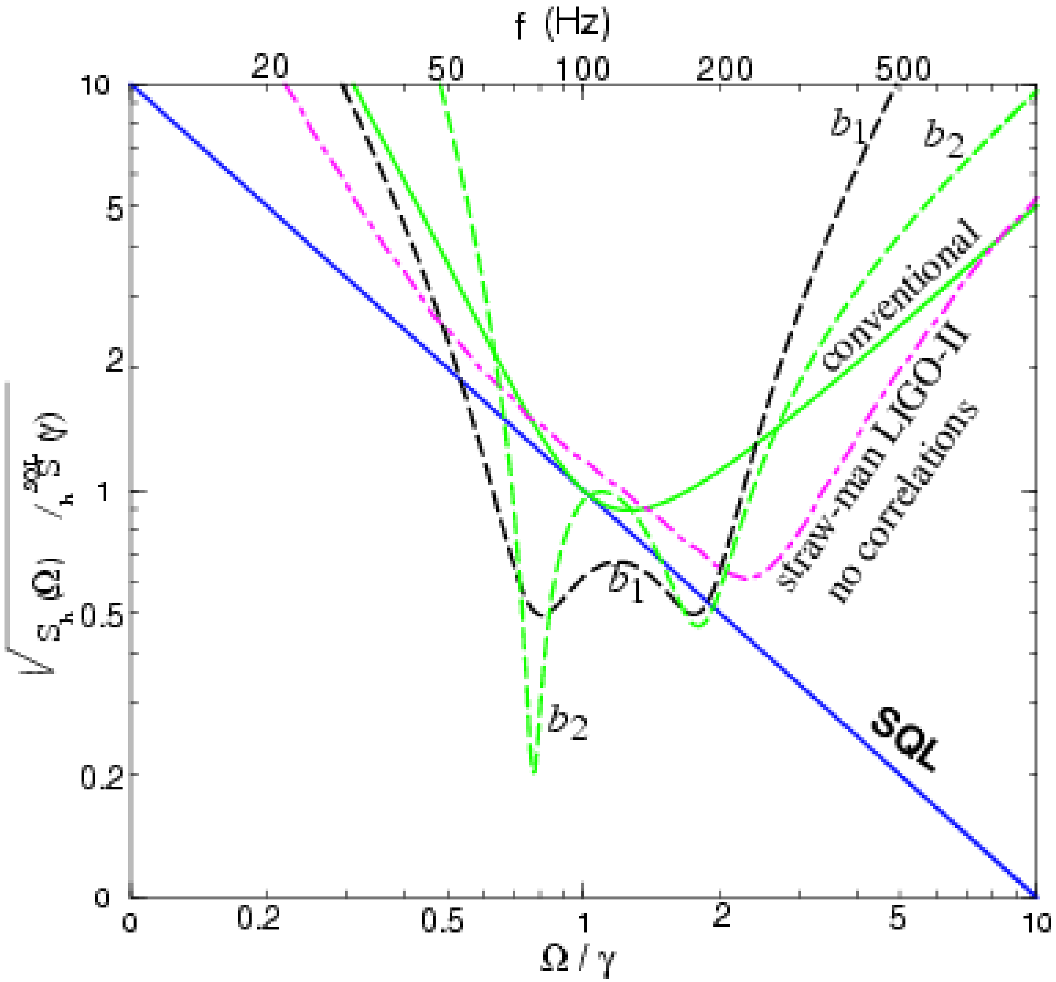
Adam Libson and Thomas Corbitt

GWADW 2015

The forgotten resonance

Optical noise correlations and beating the standard quantum limit in advanced gravitational-wave detectors

Alessandra Buonanno and Yanbei Chen 2001 *Class. Quantum Grav.* **18** L95. (2001)



Sensitivity improvement from optical spring more robust against optical loss because it amplifies signal.

Optomechanical Interactions

- Squeezed light from Atoms, silicon microchip / membranes, small squeezing <2dB around resonances
- Fundamentally important, but crystal squeezing sources pretty good for GW detectors...

What looks feasible for GW detectors 10-20 years from now?

- R&D direction: lower thermal noise, lower optical loss, not crazy to achieve in ~>10 years
- Filter cavity with ponderomotive squeezer? No clear path, but perhaps in principle (incremental)
  - → more compact, tunable, new wavelength
- Intracavity-filtering
- Amplifier (signal over noise)

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Output anti-squeezer

Speed meter


University of Glasgow
Speed meter: are we ready for it?
erc
Science & Technology Facilities Council
What is our starting point?
Squeezing injection becomes a conventional technique for GW interferometers (Recall this statement of mine and your reaction on it at GWADW 2010 in Kyoto ☺);
Emil's and Katherine's talk yesterday and Nergis's and Lisa's talks on Monday
Frequency dependent squeezing is a "must have" for any broadband sub-SQL detector, relying on back-action noise cancellation;
Lisa's talk on Monday and Tomoka's talk yesterday
Signal recycling mirror is an integral part of the majority of proposed advanced topologies, so why not assume the arbitrary detuning thereof as well?
Having said that, we:
Hope thermal and seismic noise are reduced, within 10-15 years, by the heroic efforts of our colleagues from the other workshops and concentrate on purely QN limitations
recall Haixing's talk yesterday
Take Michelson and Sagnac. Assume FD squeezing and detuned SRC in both. For each, find the optimal set of parameters to get best broadband QN noise curve
Make a fair comparison of the two and make a conclusion.
S.L. Danilishin et al. (University of Glasgow)
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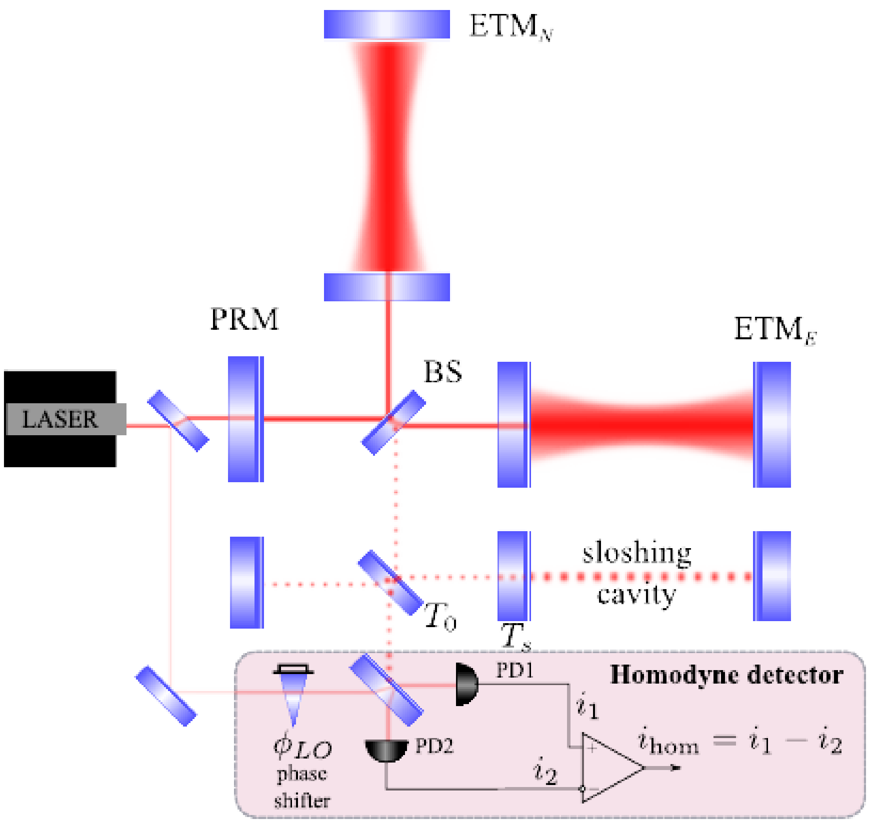
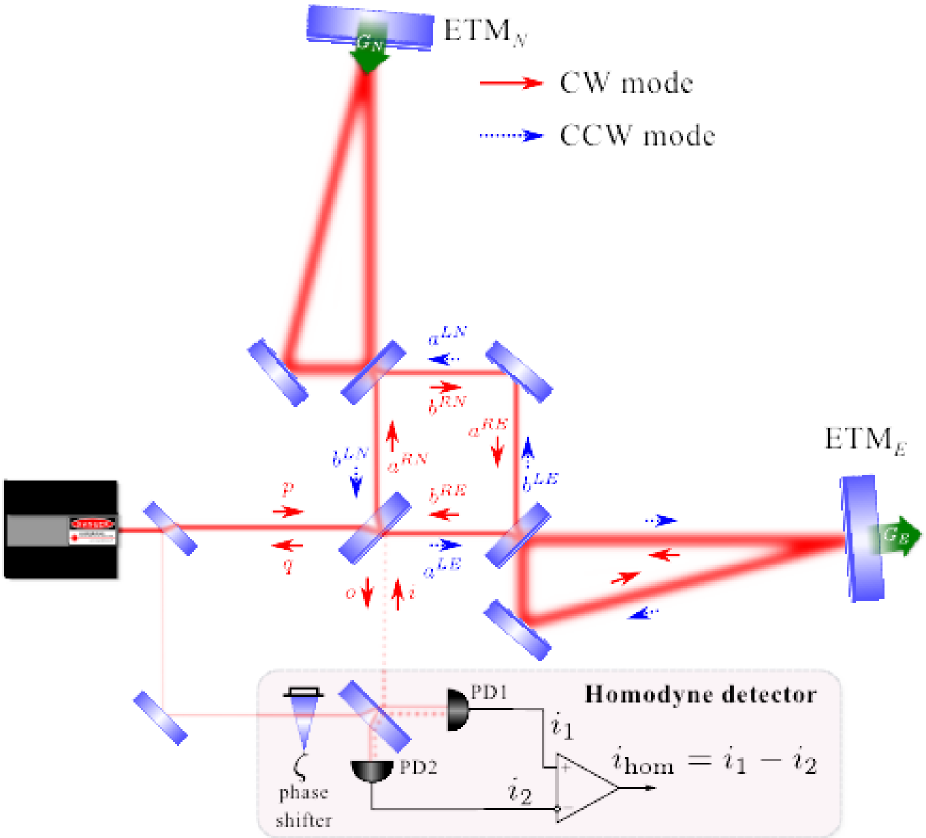
Speedmeter interferometers

Sloshing speedmeter



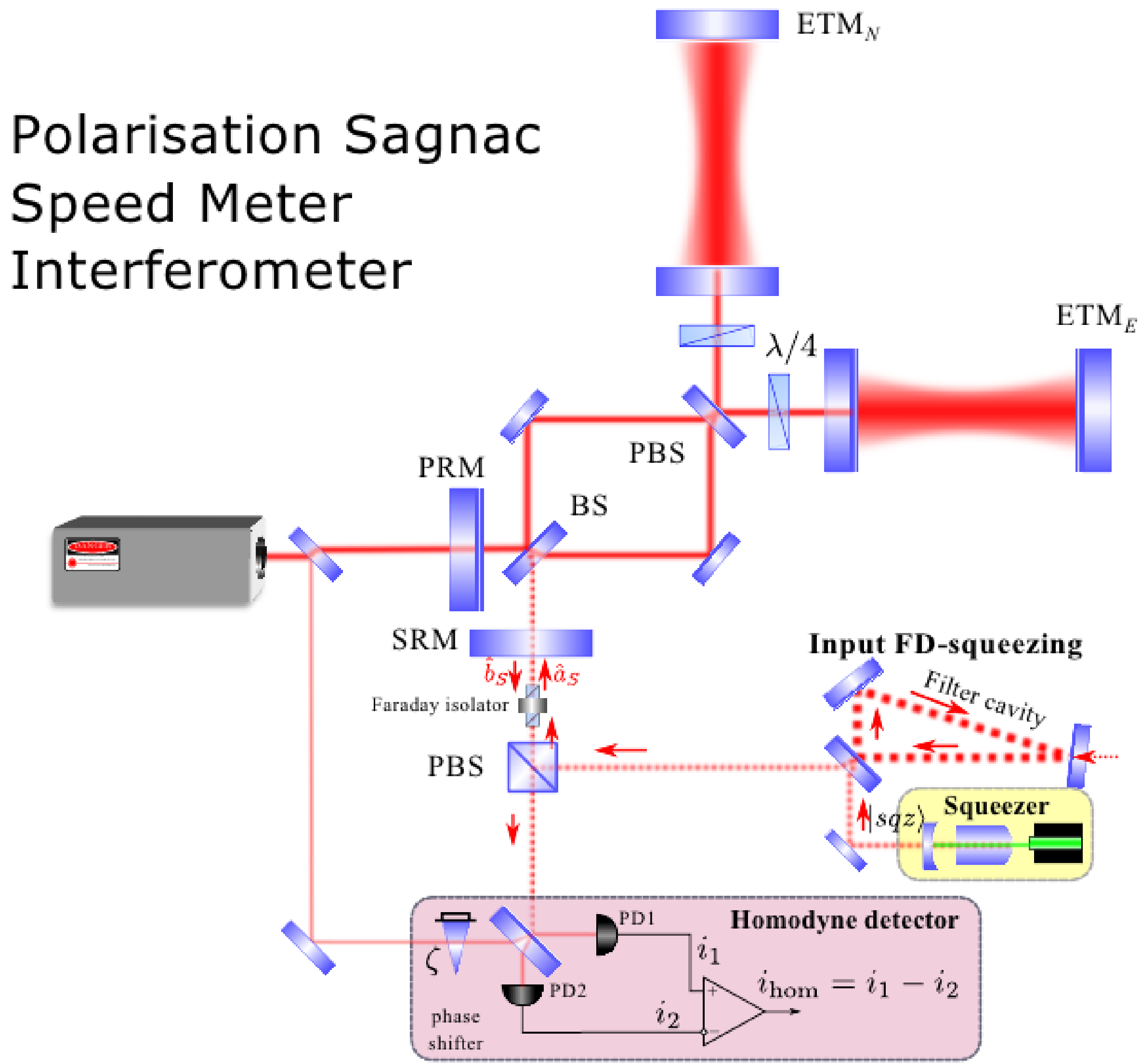
Ring arm cavities Sagnac speedmeter



- P. Purdue, Phys. Rev. D 66, 022001 (2002).
- P. Purdue, Y. Chen, Phys. Rev. D 66, 122004 (2002).
- A.R. Wade et al., Phys. Rev. D 86, 062001 (2012).

- P.T. Beyersdorf et al., Opt. Lett. 24, 1112 (1999).
- F.Ya. Khalili, arXiv:gr-qc/0211088,(2002).
- Y. Chen, Phys. Rev. D 67, 122004 (2003).

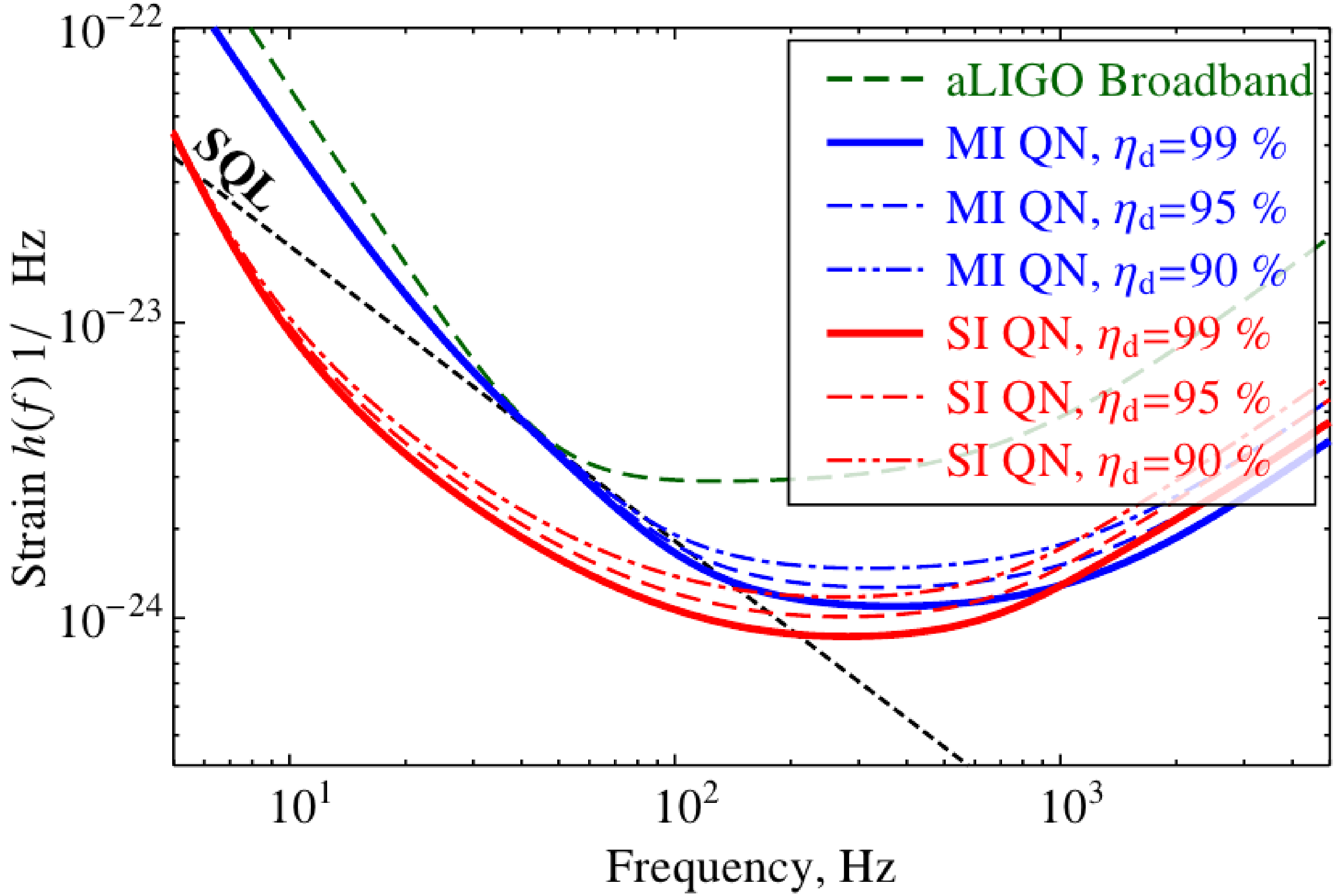
The strawman design for this study



1. Polarisation Sagnac;
2. Balanced Homodyne Readout;
3. PR and SR (SR detuned);
4. FD Squeezing (1 filter cavity);

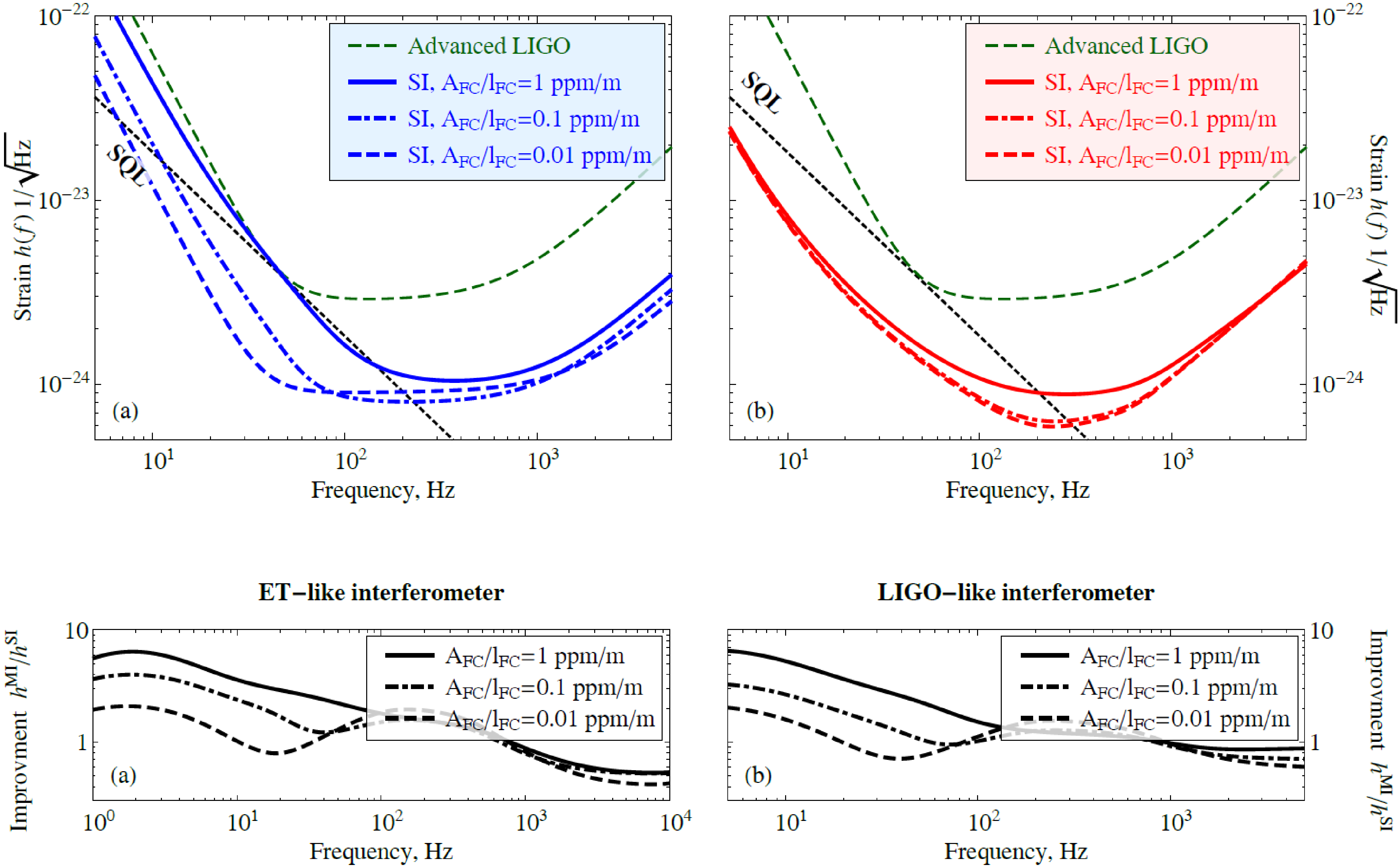
- S.L. Danilishin, Phys. Rev. D 69, 102003 (2004).
- M. Wang et al., Phys. Rev. D 87, 096008 (2013)
- N.Voronchev et al., arXiv:1503.01062 (2015)
- P. Fritchel et al., Opt. Express 22, 004224 (2014)
- M. Stefszky et al., Clas. Quant. Grav. 29, 145015 (2012)
- J. Miller et al., LIGO-P1500062 (2015)

How bad will it be if 1 % of readout loss is a too optimistic value?



Readout loss is a problem, but equally so for Michelson.

Example of considerations: Filter cavity losses



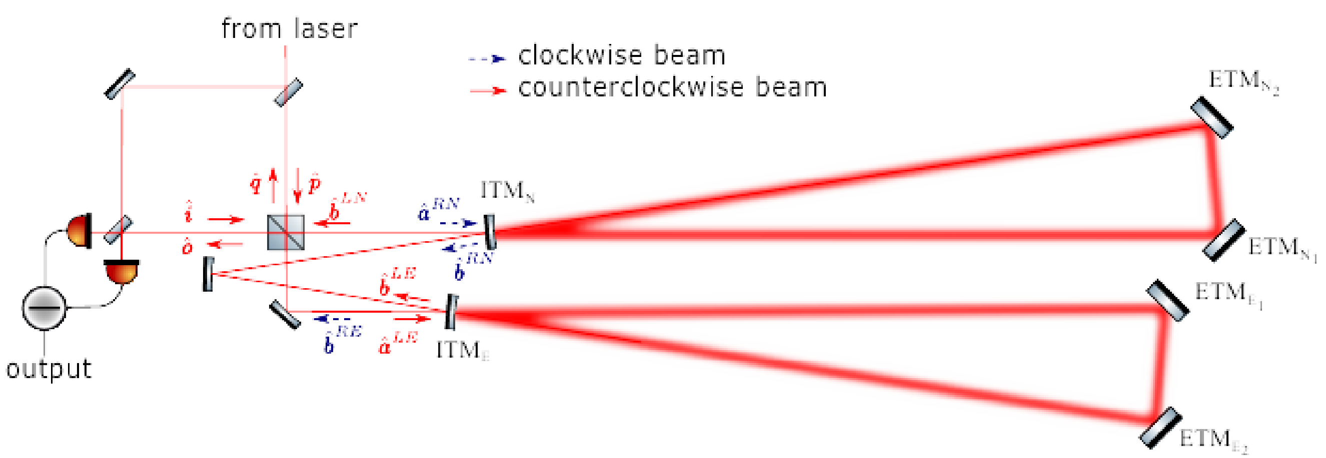
How do we know it all works?

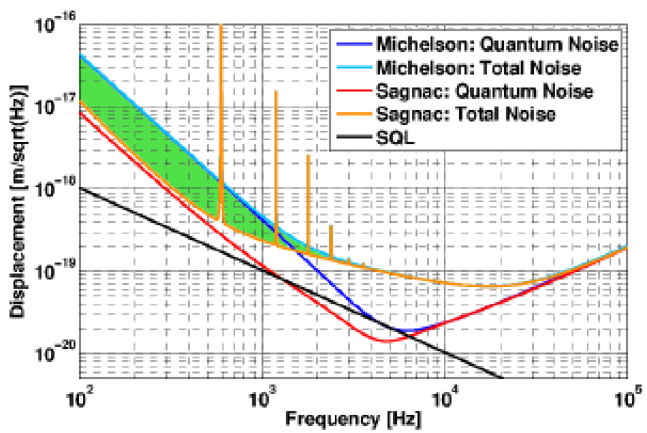
To gain credibility within the community, experimental test is crucial.

To these ends, the IGR team lead by S. Hild is building a prototype speed meter experiment funded by ERC Starter Grant scheme.

Glasgow Speed Meter major goals:

1. Create an ultra-low noise speed meter testbed which is dominated by quantum RP noise;
2. Demonstrate the reduced back-action noise of the Sagnac topology;
3. Explore speed meter technology for future GW detectors, such as ET



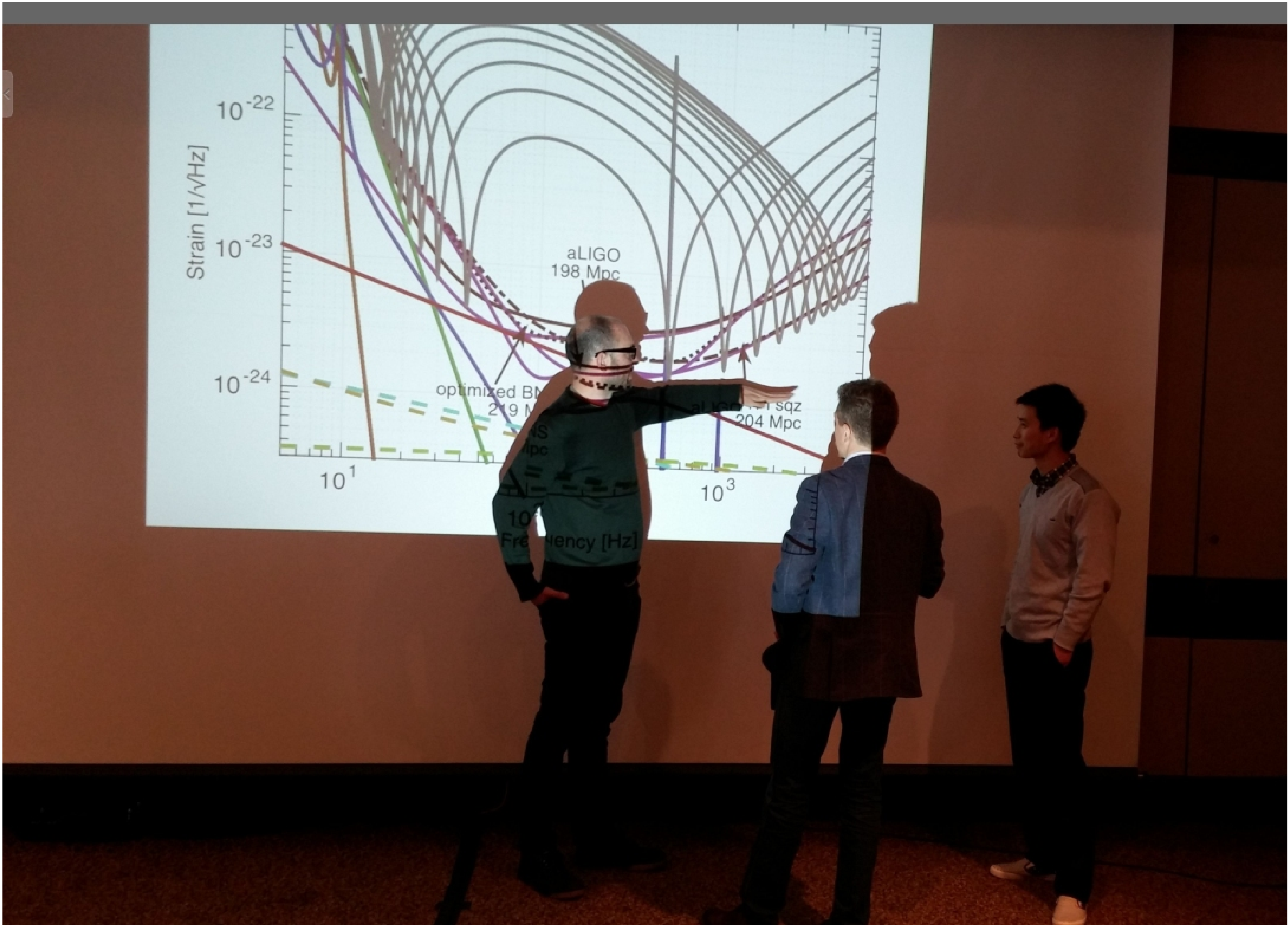


Speed meter

- Radical new topology, just at the beginning of experimental research
- High potential, mostly at low to mid-f
- Needs demonstrator at prototype level to propose for large facility
- Important to research, very good to see real dirt effects included in simulations
- Could sloshing design be incremental?

Something else

- Physics at ~1-4kHz
- Detuning feasible?



Strain [1/√Hz]
10^-22
10^-23
10^-24
aLIGO
198 Mpc
optimized BN
219 M
204 Mpc
10^1
10^3
Frequency [Hz]

Excursion: Which R&D should we pursue?

- Need broad R&D to be attractive for funding?
- Need broad R&D to select potentially useful techniques. Not always clear what can be useful and what not (even just for GW detectors)
- Question if a technique will be ready in 10-20 years large depends on effort put into it

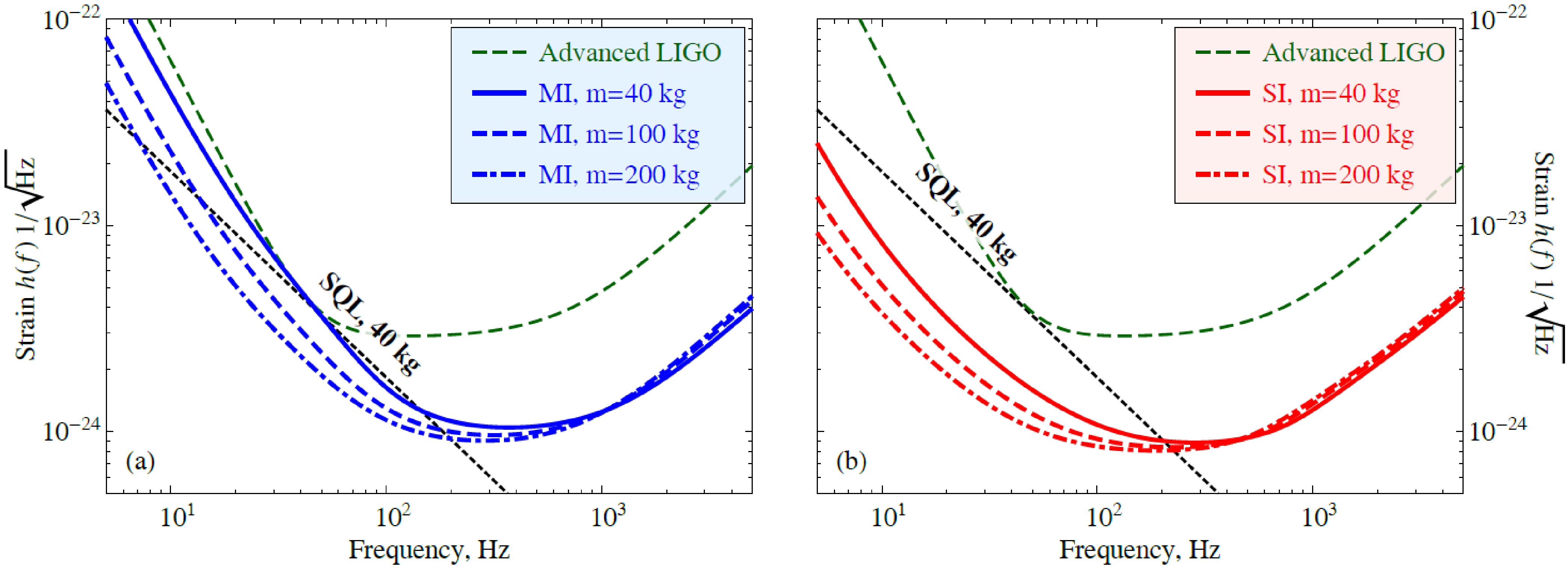
A tradeoff: Incremental or not

- Squeezing application at GW detectors readily accepted, because incremental, easy to separate and debug. Clear interface
- Incremental is helpful in many ways
(of course, tradeoff with radical new design)
- At what level do new technologies have to be demonstrated?
- What is the role of the prototypes in this?

What did we miss?

- Discussion on wavelength: prospects for high power lasers/squeezing/low loss components at other wavelengths
- …
- ...

TBC



10^{-22}
10^{-23}
10^{-24}
Strain $h(f)$ $1/\sqrt{\text{Hz}}$
Advanced LIGO
MI, m=40 kg
MI, m=100 kg
MI, m=200 kg
SQL, 40 kg
(a)
10^1
10^2
10^3
Frequency, Hz
Advanced LIGO
SI, m=40 kg
SI, m=100 kg
SI, m=200 kg
SQL, 40 kg
(b)
Frequency, Hz